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WASHINGTON

MEMORANDUM REPORT

for

Army Air Forces, Materiel Command

COOLING INVESTIGATION OF A B-24D ENGINE-NACELLE INSTALLATION IN THE NACA FULL-SCALE TUNNEL

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INTRODUCTION

At the request of the Army Air Forces, Materiel Command, an investigation has been conducted in the NACA full-scale tunnel to determine methods of improving the cooling of the B-24D engine installation. The B-24D is a four-engine high-wing monoplane having a span of 110 feet, a wing area of 1048 square feet, and a gross weight of 56,000 pounds. It is powered by four 14-cylinder Pratt & Whitney R-1830-43 single-speed, single-stage engines equipped with General Electric type B-2 turbosuperchargers. The engines have a normal rating of 1100 brake horsepower and military rating of 1200 brake horsepower at 25,000 feet altitude.

In the original engine installation of the XB-24B airplane serious cooling difficulties were encountered. It was not possible to cool normal power at altitudes above 15,000 feet and due to insufficient intercooling the carburetor-air temperature was as much as 23° F above the allowable limit. After considerable flight testing by the Consolidated Aircraft Corporation, some improvement in

cooling was attained by extending the cowl forward to reduce the clearance between the full-feathered propeller and the cowl nose from 3 inches to approximately 1/2 inch, by reducing the intercooler duct width at the cowl outlet, and by cutting back on the shroud over the exhaust collector ring to increase the effective outlet area. As a result, the cooling was sufficiently improved so that climb and level-flight operation could be continued up to 20,000 feet at 1050-brake-horsepower engine output.

Further modifications were made to the installation including the use of larger carburetor jets. With these jets the mixture to the engine was enriched by approximately 7 percent. It was then possible to provide marginal intercooling and engine cooling for 1050 brake horsepower at 25,000 feet.

The primary object of the wind-tunnel investigation has been to determine the modifications necessary to cool the engine at cruising, normal, and military power at 25,000 feet altitude. In addition, an analysis was made at the request of the Army Air Forces to determine the possibilities of obtaining satisfactory cooling with normal and military power at a critical altitude of 35,000 feet.

The tests, which were made on a single production nacelle mounted in the tunnel on a stub wing, included investigations of the engine cowling and cooling, the intercooling, the oil cooling, the turbo-supercharger installation, and the flow through the induction system. The effects on the engine temperatures of the cooling-air pressure

drop, the fuel-air ratio, and the engine power were determined. Numerous corrective modifications of the original installation were tested and their effects on the airplane performance evaluated.

APPARATUS AND METHODS

The full-scale tunnel, equipment, and methods of operation are described in reference 1. The rectangular stub wing, on which the B-24D production nacelle was mounted in the tunnel, had an area of 475 square feet, a span of 40 feet, and a chord of 12 feet (fig. 1). An 11.5-foot-diameter Hamilton Standard constant-speed propeller with blades of 6153 A-18 design was used on the installation.

The arrangement of the intercooler, the oil cooler, and the engine-air ducts is shown in figures 2 and 3. The duct for the intercooler cooling air is located on the left side of the nacelle and the ducts for the oil cooler and engine air are on the right side. The inlets to these ducts are shown in figure 4. The air passing through the intercooler and the oil cooler is dumped into the nacelle afterbody and exits through a common outlet at the tail of the nacelle (fig. 5). Some of this air also exits through leaks in the fire wall and the nacelle.

To determine the duct losses and the air quantities, total- and static-pressure measurements were made in the cooling-air and in the engine-air ducts at the shaded sections shown in figures 2 and 3. About 250 total- and static-pressure tubes were used for

these measurements. The intercooler and the oil-cooler cooling-air and the charge-air quantities were measured at sections K and Y.

The baffle pressure drop for each cylinder was determined from total-pressure measurements at the cylinder baffle inlets and from the static-pressure measurements behind the heads and the barrels of the cylinder. For purposes of comparison the front pressures were also measured with the standard Army buttons. The location of the total- and static-pressure tubes and the standard Army button used for these measurements are indicated in figures 6 and 7. The positions of the tubes at the baffle inlet were chosen to show the distribution of total pressure at the face of the engine and to indicate the effect of the modifications on this distribution.

Engine temperature measurements were made with cylinder flange and rear-spark-plug-gasket thermocouples. These temperatures were indicated and recorded by a self-balancing potentiometer. The fuel-air ratio was determined during the tests by analysis of the exhaust gases by an Orsat apparatus and a Cambridge indicator. A Pioneer fuel flowmeter and weigh tank measured the amount of fuel used by the engine. The control panel, the manometers, the Orsat exhaust-gas analyzer, the fuel flowmeter, and the Cambridge fuel-air ratio indicator were located in the test house, the interior of which is

shown in figures 8 and 9. The control panel included the instruments required for operation of the engine and the thermocouple selector switches.

The angles of attack, the propeller-blade angles, and the propeller advance ratios V/nD used in the tests corresponded to the high-speed and the cruising flight condition at an altitude of 25,000 feet and to the climb flight conditions at sea level. Because of the difference in aspect ratio between the airplane and the test wing, the angle of attack of the thrust axis rather than the lift coefficient was considered as the more fundamental variable in determining the nature of the flow into the cowling. The angles of the thrust axis for the high-speed, the cruising, and the climb conditions were -0.5°, 5.2°, and 8.5°, respectively. The propeller blade angle was set at 43° for the high-speed and the cruising conditions and at 25° for climb at the 42-inch station.

The propeller speeds were 850, 890, and 1800 rpm, respectively, for the high-speed, the cruising, and the climb conditions to give approximately the V/nDs required to simulate these flight conditions with a tunnel airspeed of 100 miles per hour.

The cowl flaps were closed in the high-speed condition and open in the climb condition. For the cruising condition the flaps were generally closed, but some tests were made in this attitude with the flap angle set at the one-quarter open, the one-half open, and the full-open positions. Except where noted, all the data

presented are for the simulated power-on flight conditions. The propeller was removed for all power-off tests.

RESULTS AND DISCUSSION

Engine Pressures

The cylinder temperatures of an air-cooled engine depend on the mass flow of cooling air passing through the fins. This flow of cooling air is dependent on the pressure difference across the engine baffles, which can be increased either by reducing the static pressures behind the engine or by increasing the total pressures in front of the engine. In the tunnel tests of the B-24D nacelle, the rear engine pressures were decreased by revising the cowl outlet and increasing the chord of the cowl flaps, and the front pressures were increased by means of blowers attached to the propeller shaft. The pressure drops measured for the production nacelle installation and the effects of various modifications are discussed in the following paragraphs.

The average front pressures referred to in the discussion are arithmetical averages of the pressures measured at the baffle inlets, a distinction being made between the head and the barrel averages in order to indicate the difference in the losses encountered. The pressures measured with the standard Army buttons are noted for purposes of comparison, but were not used in determining these averages. The pressures are given as nondimensional coefficients based on the dynamic pressure, q_o, corresponding to the tunnel airspeed.

Original condition. - The pressures in front of and behind the engine for the original production engine-nacelle installation are given in figure 10 for the high-speed and the climb attitudes and in figure 11 for the cruising attitude with four flap openings. The cowl flaps were fully open for the climb condition. The average front and rear pressures and the pressure drop for each cylinder are plotted against cylinder number for the heads in figures 12, 13, and 14 and for the barrels in figures 15, 16, and 17.

The pressures at the face of the engine in climb were especially low on the heads of cylinders 1 and 3 and on the barrels of cylinders 5 and 13, the values being $0.65\ q_o$, $0.57q_o$, $0.62q_o$, and $0.60q_o$, respectively. In high speed, the pressures on these cylinders were only slightly below the average of all the cylinders, but in cruising these front pressures were as much as $0.10q_o$ lower than the average. Opening the cowl flaps in the cruising condition reduced the front pressures by about $0.05q_o$ on most of the cylinders and by $0.15q_o$ on the barrels of cylinders 3, 5, and 13.

The front pressures on the original engine-nacelle installation in the climb condition were about $0.70q_o$ on the heads and barrels of the top cylinders and about $0.95q_o$ on the heads and barrels of the bottom cylinders. In high speed and cruising, this difference was much less as shown in figure 18 where the ratio of the average head pressure on cylinder 1 to the average head pressures of

cylinders 7, 8, and 9 is plotted against angle of attack. Increasing the angle of attack from -0.5° to 8.5° decreased this ratio by 30 percent. This reduction is due primarily to the blanketing effect of the propeller hub and blade shanks.

The front pressures on the front- and the rear-row cylinders are plotted separately in figures 19, 20, and 21, and show that the pressures on the rear cylinders, especially 1, 3, 5, and 13, are consistently lower than those on the adjacent front cylinders. The lower pressures on the rear cylinders show that part of the loss in the air entering the rear cylinder takes place just ahead of the cylinder baffles. This effect is most pronounced on the upper cylinders in climb, where the rear-row pressures are $0.10q_o$ or lower than the front-row pressures.

The static pressures behind the engine at the higher angles of attack are considerably lower on the top cylinders than on the bottom cylinders. This is attributable to the lower pressures behind the upper cowl flap resulting from the higher velocity of the flow over the top of the nacelle. This difference in back pressure somewhat counteracts the differences in the pressure recovery at the front of the cylinders at these higher angles of attack.

The pressure drops across the heads of cylinders 1, 5, and 13 in the climb condition, which are $0.96q_o$, $0.90q_o$, and $0.89q_o$, respectively, are from $0.15q_o$ to $0.20q_o$ below the values for the adjacent front cylinders. Measurements on cylinder 3 indicated a much lower

pressure drop, but leakage through the baffles near the point of measurement of the rear pressure leaves the test values in question; the questionable data have consequently been omitted.

In order to show the origin of some of these losses, power-off measurements were made of the front and rear engine pressures for the original engine-nacelle installation with the propeller removed. The distribution of the pressures with propeller removed is shown in figure 22 for the high-speed and the climb attitudes and in figure 23 for the cruising attitude at several flap angles. The average front and rear pressures and the pressure drops are given in figures 24 and 25 for high speed and climb and in figures 26 and 27 for cruising.

A comparison between the propeller-removed and the propeller-operating pressures at the heads and the barrels is made in figures 28 and 29 for the climb condition. The variation in the front pressures of the top and bottom cylinders is considerably less with the propeller removed indicating that much of the dissymmetry of the power-on distributions is caused by the wake of the round blade shanks and by the interference of the propeller hub.

The front pressures on the top cylinder were about $0.10q_o$ higher and on the bottom cylinder about $0.10q_o$ lower with propeller removed. The rear engine pressures were also slightly higher due principally to the reduction in the velocity over the cowl flaps caused by the elimination of the propeller slipstream. The

pressure drops with propeller removed were consequently much more uniform than with the propeller operating and slightly higher on the top cylinders.

In the high-speed and cruising attitudes, the front pressures were also slightly higher as is evident from a comparison of figures 10 and 22 for high speed and figures 11 and 23 for climb. Since the back pressures are not as much affected in these flight conditions by the slipstream, the pressure drop in both cases is higher with the propeller removed.

The tests on the original B-24D engine-nacelle installation were further extended to show the effect of varying propeller speed in the climb condition. The pressure distributions given in figure 30 for tests made at 1600, 1800, and 2000 rpm ($V/nD = 0.66$, 0.73, and 0.83, respectively) are compared with the propeller-removed results for the same attitude. The average front head pressures, plotted in figure 31, show that reduction of the propeller speed lowered the pressures in front of the cylinders that benefited from propeller operation and slightly improved the pressures at the critical cylinders.

<u>Original flap</u>. - The gaps between the sliding portions and at the leading edge of the original flaps were sealed to determine the effect on the rear pressures. The values presented in figure 32 show that the rear pressures in the climb condition were unaffected by these changes.

Short sections of cowl flap were added on each side of the nacelle to form a continuous flap around the nacelle. In this way any flow around the ends of the flaps from higher to lower pressure regions was prevented. The test results showed a small increase in rear pressure on the top cylinder and an equal decrease on the bottom cylinders.

Minor modifications to the existing flap, such as those referred to above, do not appear to provide any appreciable decreases in the rear pressures.

Flap modifications. - A 6-inch extension was added to the original flap, thereby increasing its chord to 16 inches. The effects of this modification are shown in figures 33, 34, and 35. The rear pressures were decreased approximately $0.10q_o$ and the pressure drops were correspondingly increased by about the same amount. In particular, the pressure drop across cylinder 1 was increased from $0.96q_o$ to $1.08q_o$ across the head and from $0.83q_o$ to $0.92q_o$ across the barrel, and the pressure drops across the heads of cylinders 5 and 13 were increased $0.09q_o$, and $0.05q_o$, respectively.

A further flap modification was made by extending the original flap 10 inches, giving a 20-inch cowl flap chord (figs. 33, 34, and 35). The modifications decreased the average rear pressure about $0.20q_o$ and increased the pressure drop by about the same amount. The pressure-drop increases for the heads of cylinders 1,

5, and 13 with the 10-inch flap extension were, respectively, $0.20q_o$, $0.14q_o$, and $0.14q_o$; the increases across the barrels were $0.18q_o$, $0.28q_o$, and $0.13q_o$, respectively.

Modified cowl outlet. - The cowl outlet was revised by removing the fairing over the collector ring, cutting away part of the fire wall and refairing the outlet as shown in figures 36 and 37, thus reducing the restriction to the flow from the cylinders to the outlet. The effect of this modification is shown in figures 38, 39, and 40. With the original cowl flap, there was a decrease in rear pressure of about $0.12q_o$ for the top cylinders and $0.05q_o$ for the bottom cylinders. With the 16-inch and the 20-inch cowl flaps, similar decreases in rear pressure were obtained. The 20-inch cowl flap with the revised outlet gave a drop of $1.28q_o$ across the head of cylinder 1, or an increase of $0.32q_o$ over the value of $0.96q_o$ for the original 10-inch flap and original outlet (fig. 41). The drops across the heads of cylinders 5 and 13 increased $0.22q_o$ and $0.20q_o$, respectively, above the original condition.

An additional test was made with the 10-inch flap extension and the modified outlet (figs. 38, 39, and 40) to check the effect of the open flap ends. Instead of continuing the flap completely around the nacelle as was previously done (fig. 32), the ends of the flap were sealed. There was a slight decrease of between $0.01q_o$ and $0.05q_o$ in back pressure with a similar increase in the pressure drop.

Although the improvement in pressure drop was thus slight, sealing the ends caused an appreciable reduction in the drag as will be shown in the drag analysis.

The increases in pressure drops for all the cylinders due to the modifications in the cowl outlet with the original and the extended cowl flaps are also summarized in tables I and II.

Modifications to increase the front pressures. - Since tests on the original engine-nacelle installation showed that the total-pressure distribution on the front of the engine was unsymmetrical and that the pressures on the top of the engine were considerably lower than those at the bottom in the climb condition, several fans were tested in an attempt to stabilize the flow into the cowl inlet and to increase the front pressures.

A spinner blower was designed and installed on the engine as shown in figures 42 and 43. A set of 27 wooden rotor blades with an NACA 6512 airfoil section was attached at the rear of a sheet-metal spinner which was bolted to the propeller hub. Each of the wooden blades was attached by a single bolt to a wooden ring which formed the rear bulkhead of the spinner. Blade-angle adjustments were made by rotating the blades around the bolts. A dishpan blower (figs. 44, 45, and 46) was constructed in simpler fashion with 36 blower blades of twisted sheet iron welded to the outer rim of the dishpan. The mean camber line of these blades was the same as that of the wooden blades of the spinner blowers. Before

the blowers were installed on the cowling (fig. 47) the cowl inlet was reworked to make it more nearly circular. The clearances at the tips of the blower blades were between 1/8 and 5/16 inch; smaller clearances, although desirable, could not be obtained without great difficulty.

A diffuser passage was constructed in the cowl from the nose opening to just ahead of the cylinders (figs. 43 and 46). In order to remove the flow rotation and recover its kinetic energy, fixed stator vanes located behind the rotor at the inlet of the diffuser were used with the spinner blower. For the first test with the dishpan blower, no stator vanes were used; one test was made, however, in which three vanes were located at the top of the engine (fig. 48) in front of the critical cylinders.

A description of the blowers and a summary of the results are also contained in reference.

The results of tests with the spinner blower are given and compared with the corresponding condition without the spinner blower in figures 49, 50, and 51. With the rotor blades set at 38° an increase in total pressure resulted at the upper right cylinders accompanied by a decrease of about equal magnitude at the lower left cylinders so that cylinder 11 now showed the least pressure drop. Conditions here are probably comparable to that of an inclined propeller which exhibits higher thrust on the side of the downgoing blade than on the side of the upgoing blade.

Increasing the rotor blade angle to 48° increased the front cylinder-head pressures in the climb condition $0.05q_o$ to $0.49q_o$, the greatest increases occurring for the bottom cylinders. The barrel pressures increased in about the same way. An additional increase was obtained with the rotor blades set at 58°, but the change was small except on the bottom cylinders where the gains were between $0.12q_o$ and $0.20q_o$. Comparison of this last condition (58° blade setting) with the corresponding condition without the spinner blower showed a net increase in front pressures for cylinders 1, 5, and 13 of $0.15q_o$, $0.36q_o$, and $0.16q_o$, respectively, with about equal increases in pressure drop.

Engine pressures were also measured with the spinner blower for the high-speed and the cruising attitudes with cowl flaps closed. These pressures are compared in figures 52, 53, and 54 with data obtained for the original nacelle installation. The comparison is permissible although conditions were not exactly comparable since the outlet area was somewhat smaller with the closed 20-inch flap than with the closed 10-inch flap (0.99 sq ft compared with 1.19 sq ft). The front pressures were increased by the blower over most of the cylinders, but not at the upper right ones. The blower blades were possibly badly stalled at this blade angle; reducing the blade angle to 48° might have resulted in appreciable improvement.

The front and rear pressures for the dishpan blower without stator vanes are given in figures 55, 56, and 57. This blower was almost as effective as the spinner blower except for cylinders 3, 4, and 5 which had front head pressures $0.14q_o$, and $0.19q_o$, and $0.30q_o$ lower than with the spinner blower.

The results for the dishpan blower with the three directional vanes (fig. 48) are shown in figures 55, 56, and 57. The total pressure in front of cylinder 1 was increased from $0.73q_o$ to $1.0q_o$ in this way, but the pressure in front of cylinder 3, which was on the lee side of the vanes, was decreased from $0.95q_o$ to $0.64q_o$.

A blower operating at propeller speed offers the possibility of substantial improvement in the pressures ahead of the cylinders with a corresponding increase in pressure drop. It is desirable to eliminate rotation aft of the blower in order that the air may be directed into the baffles without excessive losses, but in absence of a complete stator a few directional vanes correctly located at the critical cylinders may considerably improve the flow.

Power-off measurements were also made with the spinner and the dishpan nose without the rotor blades. In figure 58, these are compared in climb to the original installation with the propeller removed. The front pressures were considerably lower with both spinners, especially at the top of the engine. The comparison is not quite exact, however, since there was less air flow with the original installation which had the 10-inch flaps.

A summary of the pressure drops obtained with the modifications tested is given in table I for the heads and in table II for the barrels. With the suggested modification on the cowl outlet and the 20-inch cowl flap, it is possible to increase the pressure drop across the engine heads to $1.29q_o$, $1.11q_o$, and $1.09q_o$ on cylinders 1, 5, and 13, respectively. The addition of a spinner blower will increase these pressure drops to $1.42q_o$, $1.70q_o$, and $1.20q_o$. The use of stator vanes behind a blower is important for recovering the rotational kinetic energy.

Engine Cooling-Air Flow

The quantity of air flowing through the engine, as obtained from Pratt & Whitney test-stand data on the R-1830 series engine, is plotted in figure 59 as the mass flow in pounds per hour against the pressure drop $\sigma\Delta p$ in inches of water. It was not possible to obtain these measurements accurately on the B-24D engine-nacelle installation at the large pressure drops because of the turbulent flow at the cowl outlet with the flap open. However, for further analysis, it can be assumed that the values given in figure 59 are applicable to present installation, and since the average engine pressure drops determined with Army buttons, as was previously mentioned, checked the averages measured with the

tubes located at the baffle inlets, the quantity data can be obtained directly from pressure drops determined from the tunnel tests.

Cylinder Temperatures

Effect of pressure drop. - The relation between the pressure drops across the cylinders and the cylinder temperature is illustrated in figures 60 and 61 where the two are compared for a fixed engine-operating condition and two flap conditions. In this range of conditions, when the pressure drop was increased by about $1\frac{1}{4}$ inches, the temperatures decreased by about 23° on the heads and about 10° for the barrel. Also, in general, the lowest temperatures occur where the pressure drops are highest.

This latter relationship is shown in figure 62 where the temperatures are plotted against the pressure drops for all the cylinders. The rate of variation of temperature with pressure drop appears about the same for all the heads and for all the barrels, but the points for the different cylinders do not all fall on the same curve. For example, a curve for the rear cylinder heads 1, 7, and 9 (full line) falls nearly 20° above the curve for the front cylinder heads 8, 10, 12, and 14 (dotted line). Similarly, a curve for cylinder barrels 1, 2, 6, 7, and 9 falls about 20° above a curve for the front barrels 10, 12, and 14. The variation of cylinder temperature with pressure drop decreases at high pressure drops.

There appeared a general tendency in these and other data for the front cylinder points to fall below those for the rear cylinders, probably because the turbulence in front of the engine improves the cooling of the front cylinders. Separation between the curves for the front and the rear cylinders was very pronounced when the blower was used (fig. 63), probably because of additional cooling of the front cylinders by the swirl.

Part of the deviation of the data from the mean lines may be due to nonuniformity of the fuel-air ratio or of the quantity of charge. The main reason for the cooling difficulties of cylinder 1, however, seems to be that its pressure drop is low, for its points do not fall above the curves for others of the rear cylinders.

The variation in the head and barrel temperatures with power is shown in figure 64 for constant pressure drop. As the power is increased from 550 to 730 horsepower, the temperatures increased about 40° on the heads and about 20° on the barrels.

A correlation of temperatures and pressures by the method of reference 2 is given in figure 65.

Fuel-air ratio. - The effect of the fuel-air ratio on the cylinder temperatures for a 0.6-normal-power condition, with the dishpan blower operating, is shown in figure 66. An increase in the fuel-air ratio from 0.73 to 0.90 decreased the head temperature 25°

and the barrel temperature 15° without appreciably changing the temperature pattern. The effect is also shown in the upper two curves of figure 67 for normal power operation without the dishpan blower. Increase in fuel-air ratio from 0.109 to 0.115 reduced the head temperature by 15° to 20°. Exhaust-gas analyses for the lower power condition indicated that the fuel-air ratio was nearly the same for all the cylinders.

Some tests were also made to investigate the improvements in cooling obtainable by using very lean mixtures instead of very rich mixtures. It was found that, for cruising operation, reduction of the fuel-air ratio from 0.70 to 0.60 lowered the head temperature by 40°. These results are given in full in a separate paper (reference 3).

Full-throttle operation. - Flight-test reports of the Consolidated Aircraft Corporation have stated that, in order to avoid excessive temperatures on cylinder 1, the flights at higher powers were made with the throttle slightly less than full open. This practice obviously results in a considerable loss of critical altitude. Some studies were accordingly made of full-throttle operation in order to investigate the difficulty.

Full-throttle operation was characterized by emission of considerable black smoke from the exhaust stack and by an increased dissymmetry of the temperature pattern. The effect of throttle position on the temperature pattern at high powers is shown in

figure 67. The two runs at part throttle have similar temperature patterns, while the one at full throttle and the same manifold pressure showed a reduction in temperature for the lower cylinders and an increase for some of the higher cylinders. This temperature distribution indicates that, for this condition, the mixture delivered to the lower cylinders was enriched at the expense of the mixture delivered to the upper cylinders. The black smoke, which is characteristic of operation with excessively rich mixtures, must thus have come from the lower cylinders.

The effect of throttle position on the mixture distribution is presumably related to the effect on the flow downstream of the throttle. The poor flow past a partly open throttle creates sufficient turbulence to mix the fuel uniformly, while the smooth flow past a full-open throttle is disadvantageous in this respect.

Intercooler Investigation

In general, high carburetor-air temperatures may be reduced by either increasing the available intercooler cooling-air pressure drop or by replacing the cooler with one having a higher heat-transfer rate for the same pressure drop. On the basis of data furnished by the manufacturers, calculations have been made of the pressure drop required to obtain satisfactory carburetor-air temperatures with the Airesearch tubular intercooler originally installed in the nacelle and with a Harrison aluminum intercooler of the same outside dimensions, with which it was replaced during

the tests. In this analysis, a uniform flow distribution of both the charge air and the cooling air at the face of the cooler was assumed and the heat transfer from the duct between the supercharger and the carburetor was neglected.

The results of the calculations are presented in figure 68, which shows the variation of carburetor-air temperature with the cooling-air pressure-drop coefficient $\Delta p/q_o$ for high-speed and climb operation in Army summer air at normal and military powers. The Airesearch intercooler, results for which are shown only for normal power climb, is entirely inadequate; due to insufficient heat-transfer surface, the pressure drop required to cool the charge air to 90° F at 25,000 feet altitude could not be developed in climb, even with an outlet flap. The pressure drop required by the Harrison aluminum intercooler is $0.88q_o$ in normal power climb and $1.09q_o$ in military power climb at an indicated airspeed of 150 miles per hour. The required pressure drops for high-speed level flight are $0.55q_o$ for normal power and $0.70q_o$ for military power, both computed for an indicated airspeed of 208 miles per hour. Slightly lower pressure drops are required by a Harrison copper intercooler; in military power climb the required pressure drop is $0.95q_o$ compared to $1.09q_o$ for the aluminum cooler.

Power-on pressure measurements through the intercooler cooling-air system were made with the nacelle in the original condition (with the Airesearch intercooler). The average total pressures at

the sections shown in figure 2 are given in table III. Although a total pressure of $1.26q_o$ was available at the duct inlet in climb, due to the high losses in the duct, a total pressure of only $0.98q_o$ was realized at the face of the cooler. A pressure drop of $0.63q_o$ was measured for the climb condition which by figure 68 would result in a carburetor-air temperature about 29° F above the allowable limit when using normal power at 25,000 feet altitude. The nozzle attached to the rear of the intercooler to guid the cooling air under the fire wall was found to restrict the flow; when the nozzle was removed and air dumped into the space behind the intercooler, the pressure drop was increased $0.15q_o$.

No further tests were made with the Airesearch intercooler and when it was replaced by the Harrison aluminum cooler, the nozzle was not installed. As shown in table III, with the nacelle in the original condition but with the new intercooler (test condition 3), the pressure drop across the Harrison cooler was $0.66q_o$, which is not sufficient for climb operation at 25,000-feet altitude. Tests were then made of various modifications to improve the pressure drop by decreasing the pressures at the back of the cooler and by increasing the pressures at the front.

Measurements at the nacelle tail outlet (fig. 69) showed that there was no flow from the outlet in the climb condition and very little in high-speed and cruising flight. A study of the problem revealed that this outlet was in a high static pressure region and

most of the air leaving the oil cooler and intercooler passed through leaks in the cowling, engine fire wall, and the holes around the cowl-flap push rods instead of through the rear outlet. This diversion of the flow was especially pronounced in climb due to the low static pressure at the nacelle leakage points just behind the open cowl flaps and the high static pressure at the nacelle outlet.

Tests to improve the nacelle outlet effectiveness followed and it was found that shutting off the flow through the oil cooler (corresponding to diverting the oil-cooler flow to a different outlet), increasing the nacelle outlet area 45 percent, and adding a 12-inch-chord flap defected 30° at the nacelle outlet resulted in a decrease in back pressure on the intercooler of $0.24q_o$ and an increase in pressure drop of $0.20q_o$. With the oil cooler open and the nacelle outlet flap at 30°, the addition of a 10-inch extension on the cowl flaps gave a net reduction of $0.28q_o$ in back pressure and resulted in a pressure drop across the intercooler of $0.89q_o$. The 10-inch extension alone, without the flap at the nacelle outlet, decreased the back pressure about $0.12q_o$, while the 6-inch extension resulted in a decrease of only $0.04q_o$. Removal of the dividing vane in the duct ahead of the intercooler increased the pressure at the face of the cooler about $0.07q_o$.

As a part of the cowl outlet modification (fig. 36) previously discussed, the holes around the cowl-flap push rods were made somewhat smaller than with the original outlet and the back pressures

on the intercooler were increased somewhat as may be seen by comparing test conditions 10 and 13 (table III). With all the modifications - a 12-inch flap at the nacelle tail outlet, a separate outlet for the oil cooler, the revised cowl outlet, the 10-inch cowl-flap extension, and the dividing vane removed from the entrance duct - a pressure drop of $1.00q_o$ was obtained across the intercooler.

As for the engine, the cooling-pressure-drop coefficient for the intercooler must be considerably larger in climb than in high speed. The increase is accomplished for the engine by opening the cowl flaps when climbing and closing them in level flight. In order to utilize the cowl flaps to best advantage to reduce the back pressure on the intercooler, tests were made with the nacelle tail outlet closed and a new outlet located behind the cowl flaps as shown in figure 70. Pressure drops of $0.91q_o$ in the climb condition and $0.49q_o$ in the high-speed condition were measured. As shown in figure 68, this pressure drop in climb is evidently sufficient to provide adequate intercooling at normal power. In high speed, the rated carburetor-air temperature would probably be exceeded at normal power. The engine back pressures increased about $0.02q_o$ in climb and about $0.03q_o$ in high speed when the intercooler duct outlet was placed under the cowl flap.

Actually installing a separate oil-cooler outlet on the right side of the nacelle (see section on oil coolers) and allowing only

intercooling air to pass through the relocated nacelle outlet decreased the back pressures on the intercooler to $-0.15q_0$, increasing the pressure drop in climb to $1.02q_0$. Enlarging the outlet 50 percent gave an additional reduction of only $0.04q_0$ in back pressure and increased the Δp to $1.04q_0$. The estimated high-speed pressure drop for this condition was $0.56q_0$. It is probable that doubling the size of the outlet would have provided sufficient area for the flow from both the intercooler and oil cooler without sacrificing pressure drop and would have eliminated the necessity for a separate oil-cooler duct outlet.

With the nacelle outlet relocated as in these tests and with a separate oil-cooler outlet, or with the relocated outlet twice the original size tested, it will be possible to operate with normal power at 25,000 feet altitude with rated carburetor-air temperature and slightly above rated carburetor-air temperature with military power. (See fig. 68.) At 35,000 feet altitude, the carburetor-air temperature with normal power would be approximately 97° F in high speed and 94° F in climb while with military power the temperature would be around 100° F.

Measurements were made in the climb attitude to determine the effect of variations in thrust upon the intercooler pressure drop. With the nacelle in its original condition, total-pressure measurements at the inlet of the duct for a propeller-blade angle of 25° and V/nD's of 0.66, 0.73, and 0.83 were $1.14q_0$, $1.26q_0$, and $1.37q_0$, respectively.

The flow of the charge air through the intercooler will be discussed in the section on the engine-air induction system.

Turbosupercharger Cooling Duct

The turbosupercharger cooling duct, shown in figure 2, tapped into the intercooler cooling-air duct a short distance ahead of the intercooler, and directed cooling air at the turbine wheel and bearing housing. Test measurements indicate that about 13 percent of the air entering the intercooler, equivalent to 34.5 pounds per minute at 25,000 feet altitude, was bypassed into this duct. Of this amount, about 60 percent or 21 pounds passes between the baffle and the compressor casing and then out through the nacelle outlet; the remaining 13.5 pounds passes between the baffle and the nozzle box on the outer side of the turbosupercharger nacelle baffle. This flow more than meets the General Electric Company recommendation of 13 and 8.5 pounds per minute, respectively.

Air-Induction System

In order to simulate the flight (climb) thrust condition at a 100-mile-per-hour tunnel speed, it was necessary to maintain the same propeller constants as in flight. For this condition, however, so little air was required by the engine that the inlet-velocity ratio at the entrance to the charge-air duct was much less than that corresponding to actual flight. For this reason, the low total pressures measured at the inlet for this condition were disregarded

and it was considered that a better estimate of the ram obtainable in flight could be obtained either from the measurements in the adjacent oil-cooler duct or from measurements in the combined oil-cooler and engine-air duct after removal of the separating vane. (See fig. 71.) The latter measurements showed a total pressure of $1.20q_o$ in the engine-air duct at the point where it branched off from the combined duct.

The losses in the remainder of the engine-air duct system were determined from measurements made with the engine running at rated power and 8250 pounds of air per hour. The large pressure drop indicated across the supercharger was measured with the waste gate full open. It is of interest as an indication of the poor flow through the supercharger passages, but does not directly concern the present study; in any case, it varied considerably with slight changes in the mass flow and in supercharger speed. The losses downstream of the supercharger may be considered as nearly independent of altitude. The losses upstream of the supercharger, however, will probably increase with altitude about inversely as the air density; for example, at 25,000 feet the indicated loss of 18 pounds per square foot will become about 45 pounds per square foot.

The loss between the supercharger and a point just ahead of the intercooler is about 25 pounds per square foot and can be attributed primarily to the right-angle bend in the duct just ahead of the intercooler. The poor distribution at the face of the

intercooler, which is shown isometrically in figure 72 for a lower power condition, is further evidence of the detrimental effect of this bend. The pressure drop across the intercooler at rated power was about 68 pounds per square foot and the loss from the outlet of the intercooler to the carburetor flange was about 25 pounds per square foot.

Isometric flow patterns of the total pressures at the outlet of the intercooler and of the pressure drop are given in figures 73 and 74 for the same power condition as for the inlet pressure pattern of figure 72. While the total pressures at the inlet of the intercooler varied in this case from -122 pounds per square foot to -67 pounds per square foot, a difference of 55 pounds per square foot, giving low flow through the rear and outboard side of the intercooler, not very much variation in the total pressures was evident at the intercooler outlet. The poor distribution at the inlet probably reduces the rate of heat transfer and probably also increases the pressure drop.

A modification was made at the outlet of the supercharger as shown in figure 75 to reduce the losses caused by the right-angle bend at the outlet and to improve, if possible, the pressure distribution at the inlet to the intercooler. The total pressure distributuion at the bottom and top of the intercooler and the pressure drop across the intercooler for this condition are given in figures 76, 77, and 78. With the modified supercharger outlet

and the similar test conditions, the total pressure varied from -118 to -79 pounds per square foot, a difference of only 39 pounds per square foot, compared to 55 pounds per square foot difference on the original installation (figs. 72, 73, and 74). A comparison of the total pressures at the outlet of the intercooler for the two cases shows that the total pressure is slightly greater on the average with the modified supercharger outlet.

Although the modification to the supercharger outlet was effective in improving the flow at the intercooler somewhat, the primary cause of the nonuniform total pressure distribution is obviously the right-angle bend in the charge-air duct just ahead of the intercooler (fig. 2). Additional improvements can probably be made by proper vaning at this bend.

Oil-Cooler Investigation

Measurements were made of the pressures in the oil-cooler duct similar to those for the intercooler. As has already been pointed out, the oil-cooler and the intercooler ducts had the same outlet in many of the tests, so that the previously mentioned modifications that were made to improve the intercooler flow frequently had a parallel effect on the oil-cooler flow. The effects of these modifications on the average total pressures in the oil-cooler system are summarized in table IV. The number in the left-hand column corresponds to the number of the same modification in table III. With

the nacelle in the original condition, with the Airesearch intercooler, the pressure drop across the oil cooler in the climb condition was found to be $0.52q_o$. The recovery of total pressure at the face of the oil cooler was poor. An isometric sketch of the total pressure distribution at the face of the oil cooler for this condition is shown in figure 79. The average loss between the inlet and the oil cooler in climb was about $0.50q_o$; in high speed the loss was about $0.36q_o$. These losses are evidently due to the sharp-edge vane at the inlet of the oil cooler and the engine-air ducts, to the vane in front of the oil cooler deflecting the flow into the two small shroud cooling ducts (fig. 3), and to the poor aerodynamic properties of the duct inlet.

The addition of a nacelle flap and a 10-inch extension to the cowl flaps (condition 8) decreased the back pressure on the oil cooler $0.28q_o$ and increased the pressure drop to $0.71q_o$. Relocating the nacelle outlet behind the cowl flaps (fig. 70) and closing the tail outlet resulted in a pressure drop of $0.66q_o$ in climb, $0.33q_o$ in high speed, and $0.40q_o$ in cruise.

The effect of some additional modifications in the oil-cooler air duct are shown in table V. The pressures given for climb were made with the propeller operating, but the drag increments and some of the pressures for high speed were measured with

the propeller removed. Little difference has been observed between the pressure values for power-on and power-off operation in the high-speed condition.

A standard Airesearch oil-cooler shutter unit, consisting of a short contracting section of duct with four controllable shutters at the outlet end, was installed behind the oil cooler as shown in figure 80. The pressure drop across the oil cooler was reduced from $0.66q_o$ to $0.46q_o$ with the shutter unit. Most of this loss can be attributed to the contraction in area at the shutters rather than to the skin-friction drag of the shutters themselves because the reduction in area increases the kinetic energy of the air at the point where it is dumped into the nacelle afterbody and correspondingly increases the loss at that point.

Since the intercooler cooling air competes with the oil-cooler cooling air for passage at the common nacelle outlet, a separate oil-cooler duct outlet was tested. It consisted of a duct leading from the oil-cooler shutter unit to a 40-square-inch outlet on the right side of the nacelle (fig. 81). An 8-inch flap, deflected 30°, was used to give the required reduction in back pressure for climb. With the shutters still installed (condition 4, table V) the oil-cooler pressure drop was $0.48q_o$ in climb. At the same time the static pressure behind the intercooler was reduced $0.14q_o$, giving an increase of $o.11q_o$ in the pressure drop across the intercooler, as noted on table III, test condition 16.

In order to reduce the losses ahead of the oil cooler, the two vanes indicated in figure 82 were removed and the duct inlet was slightly modified to reduce the rate of expansion aft of the duct inlet. The losses between section Y and the face of the oil cooler were reduced by $0.09q_o$ in climb and $0.08q_o$ in high speed. The losses ahead of section Y, however, were slightly increased. These higher losses are probably due to a reduction in the inlet velocity ratio which is caused by the low quantity of charge air required by the engine in simulated flight operation, as discussed in the section on the induction system. Some improvement could be expected in flight when the engine is drawing rated power since the inlet velocities would be increased considerably in both high speed and climb.

With the shutters removed from the oil-cooler shutter unit, the pressure drop was increased $0.09q_o$ in climb and $0.03q_o$ in high speed. The fact that these differences are small substantiates the statement previously made that much of the loss due to the shutter installation was due to the restriction in area rather than to the shutters themselves.

Drag Evaluation

Power-off force measurements were made to determine the effect upon the airplane drag of the various modifications made to increase the cooling-air flow through the engine, the intercooler, and the oil cooler. To establish a basis for comparison,

the drag of the wing-nacelle installation was measured with the turbosupercharger completely enclosed and the inlets and the outlets of the cooling-air and the charge-air ducts and the engine cooling-air passages completely sealed (fig. 83).

Lift and drag polars, based on the 475-square-foot area of the test wing, are given in figure 84 for the major modifications. The drag coefficients for the simulated high-speed and climb conditions are presented in table VI, together with the increments in drag coefficient due to the modifications and the corresponding increments for four nacelles, based on the B-24D wing area of 1048 square feet. A lift coefficient for the test wing of 0.18 was used to simulate high speed and a lift coefficient of 0.60 to simulate climb with cowl flaps open. The angle of attack used to represent the climb attitude gave a lift coefficient of 0.70, but 0.6 was chosen for the power-off climb comparison of drags because the curves flattened out at the higher value with flaps open.

Original nacelle installation. - The wing-profile-drag coefficient which was measured by the wake-survey method at several spanwise sections outboard of the nacelle, was 0.0097 in the high-speed attitude. Adding the estimated induced drag of the stub wing for a lift coefficient of 0.18 gave a total wing drag coefficient of 0.0128.

As shown in table VI, four completely faired nacelles (fig. 83) added to the wing will increase the airplane drag coefficient by about 0.0064. With the fairing removed from the supercharger and from the section of exhaust pipe between the collector ring and the supercharger (fig. 85), the drag coefficient was increased 0.0040 over that for the completely faired nacelle in the simulated high-speed condition. Removing the seals on the cooling-air and charge-air ducts further increased the drag by 0.0020. Since, for these power-off tests, there was no flow in the charge-air duct, this increment is due primarily to the air flow through the intercoolers and the oil cooler. By unsealing the engine cooling-air inlet and outlet (fig. 4) the nacelle was brought to the original flight condition. The drag coefficient for this condition in high speed was 0.0093 more than for the nacelles completely faired or a total increase of 0.0133.

Opening the original cowl flaps, in the climb attitude, increased the airplane drag coefficient by 0.0210.

Cowl outlet and flap modification. - The modifications to the cowl outlet and the cowl flaps had very little effect on the drag in the high-speed attitude since the external shape of the nacelle remained unaltered. The slight decrease of 0.0004 in airplane drag which is indicated for the revised cowl outlet and 20-inch flaps in the closed position can be attributed to a slightly smaller outlet area and the consequent reduction in flow through the engine.

In the climb attitude, the revised cowl outlet with the original 10-inch flap increased the drag coefficient 0.0016. This is probably due solely to the increase in the engine cooling-air flow which was indicated by the reduction in engine back pressure (fig. 39). The 6-inch cowl-flap extension fully deflected increased the drag coefficient 0.0118 over that obtained with the original cowl-flap installation, while the 10-inch extension gave an increase of 0.0336.

The effect of flap angle on the airplane drag coefficient in cruising is shown in figure 86 for the three flap installations together with the variation in the engine pressure-drop coefficient for the original 10-inch flap. The rate of increase in drag coefficient becomes greater at the larger flap angles while the rate of increase in pressure drop becomes smaller. The flap effectiveness therefore decreases with increasing flap angle.

The addition of a 12-inch flap on the nacelle outlet gives an increase of 0.0009 in the high-speed attitude and 0.0045 in the climb attitude when used in conjunction with the 20-inch cowl flap.

Modifications to oil-cooler and intercooler systems. - For the original installation, the drag of the intercooler and the oil cooler with the common nacelle outlet, including both the internal and the external drag, was 0.0020. Relocating the nacelle outlet, which increased the flow through both the oil cooler and the intercooler, gave a reduction in drag coefficient of 0.0004.

The addition of the separate oil-cooler outlet further increased the flow through the intercooler and the oil cooler and showed an additional decrease in drag coefficient of 0.0002 in high speed. The installation of the oil-cooler shutters increased the duct losses and reduced the flow without any appreciable change in drag.

With the relocated nacelle outlet and the separate oil-cooler outlet, sealing the intercooler duct reduced the drag by 0.0007 and sealing the oil-cooler duct reduced the drag by the same amount.

Supercharger modifications. - A summary of the effects of the modifications to the turbosupercharger installation, power-off, is given in table VI(c). In these tests, flight conditions were not perfectly simulated as no exhaust gases were flowing from the turbine wheel; it is believed, however, that the measurements give some indication of the flight drag increments.

A view of the bottom of the nacelle, showing the exposed turbine and exhaust pipe in the original condition, is given in figure 85. As previously shown (table VI(a)), the turbine and the exhaust pipe increase the drag of the airplane approximately 0.0040. Adding the turbine hood (fig. 87) increased the drag 0.0002, making the total drag of the installation 0.0042. The new afterbody as originally installed (fig. 88) increased the drag increment 0.0075. This large increase in drag is attributed to the poor shape of the afterbody and to air leakage through the holes and gaps. With

an afterbody of such poor shape, the leakage was evidently sufficient to cause the flow to separate from the nacelle surface. Sealing all the leaks in the afterbody (fig. 89) reduced the drag of the turbosupercharger installation to 0.0027.

This increment of 0.0027 must be due to the exhaust pipe, the projection of the turbine hood down into the air stream, and to the poor shape of the afterbody. Further reductions in drag can probably be attained by raising the supercharger and enclosing it in an afterbody of better shape and by eliminating the roughness on the bottom of the nacelle caused by the exhaust pipe, mounting brackets, etc.

A sketch of a recommended afterbody and a method of supplying cooling air to the exhaust pipe and turbine scroll is shown in figure 90. Although such an installation requires raising the supercharger, the space seems to be available and the possibility of reducing the airplane drag coefficient between 0.0030 and 0.0040 makes such a change highly desirable. In this installation, the inlet for the exhaust-shroud cooling air is located between the rocker boxes of cylinder 7. An alternate location for the inlet is at the baffle between the cowling and cylinder 6. The elimination of the present shroud cooling ducts will result in an improvement in the air flow in the oil-cooler duct.

It is difficult to estimate the cooling-air requirements for the exhaust pipe, but since the recent development of turbine materials which are better able to withstand high exhaust-gas temperatures this

may not be so critical as it has been in the past. A radiation-type cooling cap and, if available, a turbine equipped with sealing rings to prevent cooling-air leakage into the buckets should be used to reduce the possibility of afterburning. The use of a new elbow at the compressor inlet will be necessary. A design of such an elbow is shown in figure 91.

Power-on drag coefficients. - Power-on drag measurements were also made of the modifications to improve the intercooling, oil cooling, and engine cooling-air flow. The power-on drag coefficients given in table VII were corrected to a V/nD of 0.75 and to a lift coefficient of 0.70 for purposes of comparison, but the values may be in error by as much as ± 0.0005 due to the nature of the variables encountered in power-on tunnel testing. The table also shows the effect of some of the modifications upon the airplane rate of climb at 25,000 feet. For comparison with the measured drag increments, values of the increments corresponding to the changes in internal pump work are also given. The lift coefficient, measured in all cases at the same effective angle of attack and at approximately the same V/nD, is also included to show the effect of the modification on the lift of the test wing.

The increment in drag attributable to the 6-inch flap extension in power-on climb is about the same as for power-off climb, as shown in figure 86, while the increment for the 10-inch flap extension in climb is 0.0085 lower with power on. This may be

attributed to the effect of the slipstream in delaying the breakdown in lift occasioned by the 20-inch cowl flaps. The rate of climb at 25,000 feet is reduced approximately 270 feet per minute with the 6-inch extension and 610 feet per minute with the 10-inch extension. It is estimated from figure 86 that the 20-inch cowl flap deflected to 16° and the 16-inch cowl flap deflected to 22° would give approximately the same drag increment in power-on climb as the original 10-inch fully deflected cowl flap with the modified cowl outlet; a slightly larger pressure drop, however, is indicated for the longer flaps. The 20-inch flap deflected 21° has about the same drag as the 16-inch fully deflected flap, but showed no appreciable difference in the available pressure drop.

It has already been noted that engine-pressure measurements made with the ends of the 20-inch cowl flaps sealed (fig. 37) showed no appreciable increase in the average pressure. The power-on drag measurements, however, indicate that the corresponding improvement in flow effected a reduction of 0.0084 in the airplane drag coefficient as well as an increase in lift coefficient from 0.691 to 0.713 (table VII). This will improve the rate of climb by 200 feet per minute compared with the 20-inch flap without the ends sealed.

The lift coefficient of 0.733 for the original condition with flaps closed was reduced to 0.721 on opening the cowl flap. This was further reduced to 0.715 with the 6-inch extension and to 0.698 with the 10-inch extension, indicating considerable disturbance over the surface of the wing behind the flap.

For all these cases mentioned, the table shows that the increment of drag coefficient obtained with flap deflection greatly exceeded the value corresponding to the increment of internal pump work $Q\Delta p$.

The spinner blower with the rotor blades at 58° increased the airplane drag coefficient by 0.0097, while the dishpan blower with the same blade angle increased it only 0.0069. The fact that blower operation, although requiring a power input to the blower, resulted in increased drag is unusual, but occurred in this case as a result of the large flap deflection and corresponding low energy of the air at the exit; blower operation merely served to increase the quantity of air flow, but did not serve to increase its total pressure at the exit. Presumably, if the flap deflection had been decreased when the blower was used, so as to maintain constant air flow, there would have been a net reduction in drag.

The power-on oil-cooler drag measurements were made with the 20-inch cowl flap open and the relocated nacelle outlet as a basic condition. Adding the separate oil-cooler outlet, with the oil-cooler flap closed, while not giving sufficient pressure drop across the oil cooler, reduced the airplane drag by 0.0016 and increased the pressure drop across the intercooler by $0.10q_o$. Opening the oil-cooler flap increased the airplane drag 0.0029 above that for the basic condition. At altitude the oil-cooler flap will probably be in the closed position since a lower pressure

drop will be required. Removing the shutters and refairing the ducts decreased the drag 0.0007 for the condition with the oil-cooler flap open.

Cooling at Altitude

Based on the full-scale tunnel test data and on flight test results, calculations have been made of the pressure required and the pressure available for cooling the B-24D production nacelle at altitude. The results are summarized in figure 92 which shows the required and available cooling pressures for four different power conditions. The values of the available cooling pressure are based on flight test data obtained by the Consolidated Aircraft Corporation; the pressures given are those available between the inlet of the baffles and the baffle outlets and do not include the loss in pressure between the inlet of the cowling and the baffle entrance. The values of the pressure required to cool are based on sea-level test data that are extrapolated to altitude by a method of analysis taking into account the density changes across the engine; the results are in reasonable agreement with liminted flight test data. Two curves of required cooling pressure are shown, one of which is the average pressure across the engine required to cool the hottest cylinder to the temperature limit, and the other the required engine pressure drop if all the engine cylinder temperatures were the same. Data are given for airplane gross weights of 48,000 and 56,000 pounds with the cowl flap closed and deflected 10°.

The most critical cooling occurs in cruising for which condition the allowable head temperature limit is 450° F. With an airplane gross weight of 56,000 pounds and with the cowling flaps closed, the results indicate that insufficient pressure drop is available to cool the hottest cylinder even at the ground, and with the 10° cowl-flap setting, the pressure drops available are only sufficient to cool the engine to an altitude of about 10,000 feet. If auxiliary means are used to cool the hot cylinders to the average temperature, the engine would cool to an altitude of about 20,000 feet with flaps deflected. A rapid increase in the pressure required for cooling occurs at altitudes above 25,000 feet so that the pressure available to cool in cruising is deficient by about 10 inches of water at 35,000 feet.

Modifying the cowling outlet by cutting back on the shroud over the exhaust pipe will increase the pressure drop across the engine and improve the possibility of cooling at 25,000 feet altitude, but none of the tested modifications to the production nacelle will enable the engine to be cooled at 35,000 feet. Cooling the B-24D airplane at a critical altitude of 35,000 feet will not be possible without improving the finning on the cylinder heads and equalizing their temperatures. A fan in the cowling inlets turning several times propeller speed will be a substantial aid.

In lieu of changes to the engine it may be possible to increase the allowable temperature limit for short-time cruising

at high altitudes by decreasing the period between overhauls. This decision and the responsiblity for providing engine cooling at high altitude seems to rest with the engine manufacturer. The present difficulties with the B-24D cooling at altitude are most directly attributed to insufficient cylinder-head finning on the Pratt & Whitney R-1830 engine.

SUMMARY OF RESULTS

Engine Cooling

1. The temperature variations among the cylinders in the same bank are primarily due to the variations in the cylinder pressure drops.

2. These variations in pressure drop are due mainly to the poor flow into the cowling at the higher angles of attack and in part to the irregularities in engine baffling.

3. The pressure drops across the critical cylinders 1, 5, and 13 were increased about $0.12q_o$ in climb by cutting back on the shroud over the exhaust pipe.

4. Increasing the flap chord to 16 inches and 20 inches further increased the pressure drop across these cylinders by $0.10q_o$ and $0.20q_o$, respectively.

5. Further increases in pressure drops of $0.10q_o$, $0.27q_o$, and $0.14q_o$ were obtained across the heads of cylinders 1, 5, and 13, respectively, by using an axial-flow fan operating at propeller speed. A rotor-stator combination was somewhat better that a rotor alone.

6. An increase in fuel-air ratio from 0.073 to 0.090 for cruising power resulted in a decrease of approximately 25° F in head temperatures and 15° F in barrel temperatures.

7. For cruising power, reduction of the fuel-air ratio from 0.70 to 0.60 lowered the head temperature 35°.

8. Full-throttle operation results in increased dissymmetry of the temperature pattern, probably due to nonuniformity of the mixture distribution.

9. Cooling the B-24D in cruising at a critical altitude of 35,000 feet will not be possible without improving the finning on the cylinder heads and equalizing their temperatures.

Intercooling at 25,000 Feet

1. The Airesearch intercooler has insufficinet heat-transfer surface to cool the engine air to 90° F at 25,000 feet.

2. The Harrison aluminum intercooler requires a pressure drop of $1.09q_o$ in climb and $0.70q_o$ in high speed to give a carburetor-air temperature of 90° F with military power at 25,000 feet.

3. For the original condition, the pressure drop across the intercooler in climb was only $0.63q_o$.

4. By removing the nozzle attached to the rear face of the intercooler, separating the intercooler duct from the oil duct, and locating its exit under the 20-inch cowl flap, the pressure drop across the intercooler was increased to $1.04q_o$ in climb

and $0.65q_o$ in high speed. These pressure drops will provide a carburetor-air temperature of 91° F at 25,000 feet.

Intercooling at 35,000 Feet

1. A Harrison intercooler approximately 15 percent larger in the no-flow direction will be required to give a 90° temperature at the carburetor for military power at 35,000 feet with a pressure drop of $1.04q_o$ in climb and $0.65q_o$ in high speed.

2. With the present size Harrison intercooler and an available pressure drop of $1.04q_o$ for climb and $0.65q_o$ for high speed, carburetor-air temperatures can be maintained at 100° F with military power and at 95° F with normal power at 35,000 feet.

Oil Cooling

1. The pressure drop across the oil cooler was increased about 25 percent in the climb condition by relocating the nacelle outlet behind the 20-inch cowl flaps and removing the dividing vanes between the oil-cooling duct and the charge-air and shroud cooling-air ducts.

2. A separate oil-cooler outlet on the side of the nacelle gave satisfactory cooling and improved the control of the flow.

3. The contraction of the oil-cooler passage at the section containing the shutters caused a considerable reduction of pressure across the oil cooler.

Engine-Air Induction System

1. The velocity and pressure distributions at the intercooler inlet on the engine-air side was very poor.

2. Modifying the supercharger outlet showed only a slight improvement in the distribution at the intercooler.

Drag

1. The cost, in drag, of the increased pressure drops obtained with the most important modifications are:

Modification	ΔC_D
Modified cowl outlet, 10-inch flap extension	0.0290
Dishpan blower	0.0069
Intercooler outlet under cowl flap, oil-cooler outlet on side of nacelle, oil-cooler outlet flap closed	-0.0016
Intercooler outlet under cowl flap, oil-cooler outlet on side of nacelle, oil-cooler outlet flap open	0.0029

2. The addition of end seals on the 20-inch cowl flaps reduced the airplane drag coefficient by 0.0089 without changing the pressure drop.

3. Enclosing the turbosupercharger within the nacelle effects an appreciable reduction in drag.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 4, 1942.

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TABLE I

SUMMARY OF THE AVERAGE PRESSURE DROPS ACROSS THE CYLINDER HEADS.

CLIMB ATTITUDE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

Test conditions				Pressure drop, $\Delta p/q_o$													
				Cylinder number													
No.	Flap	Cowl outlet	Miscellaneous	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Original	Original	--------------------	0.96	1.07	----	1.03	0.89	1.18	----	1.12	1.13	1.22	1.05	1.14	0.89	1.08
2	6-inch extension	Original	--------------------	1.08	1.26	----	1.18	.98	1.33	1.15	1.27	1.24	1.36	1.16	1.27	.94	1.28
3	10-inch extension	Original	--------------------	1.16	1.37	----	1.27	1.03	1.40	1.22	1.36	1.36	1.49	1.26	1.41	1.03	1.38
4	Original	Modified	--------------------	1.08	1.24	----	1.14	.94	1.26	1.07	1.19	1.19	1.27	1.07	1.25	.95	1.25
5	6-inch extension	Modified	--------------------	1.21	1.39	----	1.33	1.05	1.35	1.14	1.27	1.31	1.42	1.18	1.40	1.02	1.40
6	10-inch extension	Modified	--------------------	1.29	1.49	----	1.38	1.11	1.40	1.22	----	1.40	1.51	1.29	1.51	1.09	1.51
7	10-inch extension	Modified	Spinner blower at 38°	1.50	1.60	----	1.50	1.33	1.39	1.13	1.21	1.16	1.18	1.04	1.37	1.05	1.44
8	10-inch extension	Modified	Spinner blower at 48°	1.43	1.69	----	1.75	1.57	1.68	1.58	1.49	1.48	1.45	1.30	1.60	1.20	1.58
9	10-inch extension	Modified	Spinner blower at 58°	1.42	1.65	----	1.78	1.70	1.92	1.58	1.75	1.65	1.57	1.36	1.62	1.06	1.59
10	10-inch extension	Modified	Dishpan blower at 58°	1.39	1.78	----	1.61	1.38	1.95	1.67	1.78	1.78	1.64	1.54	1.76	1.23	1.96
11	10-inch extension	Modified	Dishpan blower, vanes ahead of cylinder 1	1.67	1.94	----	1.66	1.44	1.96	1.69	1.75	1.79	1.68	1.54	1.75	1.25	2.01

TABLE II

SUMMARY OF THE AVERAGE PRESSURE DROPS ACROSS THE CYLINDER BARRELS,

CLIMB ATTITUDE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

Test conditions				Pressure drop, $\Delta p/q_o$													
				Cylinder number													
No.	Flap	Cowl outlet	Miscellaneous	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Original	Original	--------------------	0.83	0.89	----	0.77	0.68	0.86	0.98	----	1.01	0.80	0.96	0.78	0.70	0.73
2	6-inch extension	Original	--------------------	.92	.99	----	.84	.89	1.02	1.07	----	1.08	.80	1.06	.82	.75	.89
3	10-inch extension	Original	--------------------	1.00	1.10	----	.94	.96	1.10	1.16	----	1.19	.93	1.21	.91	.83	.95
4	Original	Modified	--------------------	.92	1.00	----	.82	.76	.98	1.04	----	1.06	.75	1.01	.80	.79	.88
5	6-inch extension	Modified	--------------------	1.03	1.11	----	.96	.82	1.08	1.11	----	1.14	.84	1.13	.91	.83	1.00
6	10-inch extension	Modified	--------------------	1.09	1.22	----	1.01	.86	1.12	1.18	----	1.21	.91	1.20	.99	.91	1.04
7	10-inch extension	Modified	Spinner blower at 38°	1.18	1.35	----	1.19	.95	1.23	1.15	----	1.14	.80	.93	.89	.95	1.01
8	10-inch extension	Modified	Spinner blower at 48°	1.21	1.46	----	1.36	1.19	1.47	1.39	----	1.41	1.08	1.18	1.03	1.06	1.11
9	10-inch extension	Modified	Spinner blower at 58°	1.23	1.43	----	----	1.21	1.63	1.56	----	1.58	1.15	1.28	1.08	1.09	1.15
10	10-inch extension	Modified	Dishpan blower at 58°	1.16	1.12	----	.92	.94	1.46	1.75	----	1.41	1.09	1.45	1.09	1.05	1.04
11	10-inch extension	Modified	Dishpan blower, vanes ahead of cylinder 1	1.44	1.36	----	.98	.98	1.48	1.80	----	1.42	1.08	1.44	1.12	1.10	1.18

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TABLE III

EFFECT OF MODIFICATIONS UPON AVERAGE TOTAL PRESSURE THROUGHOUT THE INTERCOOLER SYSTEM

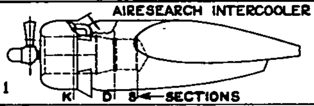
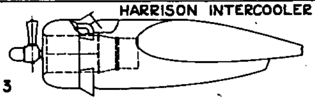
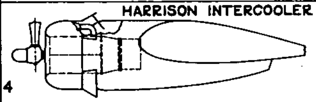
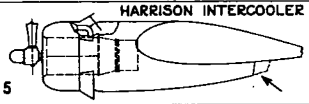
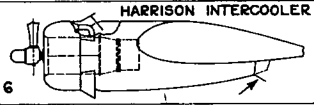
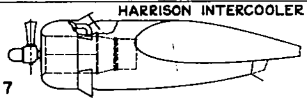
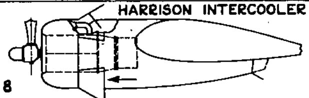
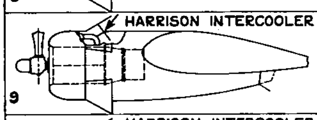
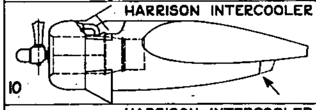
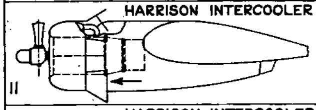
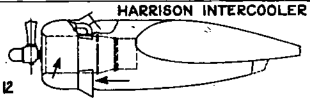
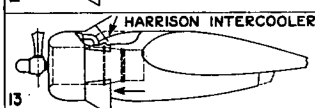
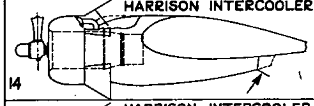
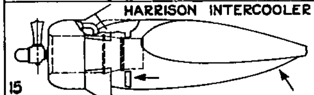
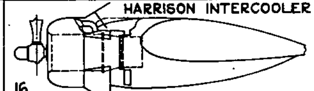
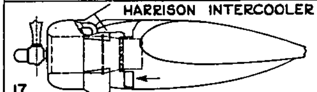
TEST CONDITION	MODIFICATIONS: NACELLE OUTLET	MODIFICATIONS: COWLING OUTLET	MODIFICATIONS: MISCEL.	ATTITUDE	AVERAGE TOTAL PRESSURE AT DUCT SECTIONS H/q_0: INLET	K	D	S	$\Delta P/q_0$
1 AIRESEARCH INTERCOOLER  K D S ← SECTIONS	ORIGINAL	ORIGINAL		CLIMB	1.26	1.06	0.98	0.35	0.63
				HIGH SPEED	.96	.93	.87	.36	.51
				CRUISE	.95	.88	.84	.40	.44
2 AIRESEARCH INTERCOOLER 	ORIGINAL	ORIGINAL	NOZZLE REMOVED	CLIMB	1.26	1.05	0.95	0.17	0.78
				HIGH SPEED	.97	.94	.86	.20	.66
				CRUISE	.93	.88	.83	.26	.57
3 HARRISON INTERCOOLER 	ORIGINAL	ORIGINAL		CLIMB	1.24	1.03	0.90	0.24	0.66
				HIGH SPEED	.98	.93	.83	.24	.59
				CRUISE	.95	.87	.79	.29	.50
4 HARRISON INTERCOOLER 	ORIGINAL	ORIGINAL	OIL COOLER SEALED	CLIMB	1.23	1.01	0.90	0.18	0.72
				HIGH SPEED					
				CRUISE					
5 HARRISON INTERCOOLER 	ENLARGED 45 %	ORIGINAL	OIL COOLER SEALED	CLIMB	—	1.03	0.90	0.17	0.73
				HIGH SPEED					
				CRUISE					
6 HARRISON INTERCOOLER 	ENLARGED 45 % 12 INCH FLAP	ORIGINAL	OIL COOLER SEALED	CLIMB	1.25	1.00	0.86	0.00	0.86
				HIGH SPEED					
				CRUISE					
7 HARRISON INTERCOOLER 	ENLARGED 45 % 12 INCH FLAP	ORIGINAL	OIL COOLER OPEN	CLIMB	1.27	1.02	0.85	0.08	0.77
				HIGH SPEED					
				CRUISE					
8 HARRISON INTERCOOLER 	ENLARGED 45 % 12 INCH FLAP	10 INCH COWL FLAP EXTEN.		CLIMB	1.24	0.98	0.85	-.04	0.89
				HIGH SPEED					
				CRUISE					
9 HARRISON INTERCOOLER 	ENLARGED 45 % 12 INCH FLAP	10 INCH COWL FLAP EXTEN.	PUSH ROD HOLES SEALED	CLIMB	1.24	0.98	—	-.03	—
				HIGH SPEED					
				CRUISE					
10 HARRISON INTERCOOLER 	ENLARGED 45 % NO FLAP	10 INCH COWL FLAP EXTEN.		CLIMB	1.23	0.99	—	0.12	—
				HIGH SPEED					
				CRUISE					
11 HARRISON INTERCOOLER 	ENLARGED 45 % NO FLAP	6 INCH COWL FLAP EXTEN.		CLIMB	1.25	1.01	0.90	0.20	0.70
				HIGH SPEED					
				CRUISE					
12 HARRISON INTERCOOLER 	ENLARGED 45 % NO FLAP	ORIGINAL	DIVIDING VANE REMOVED	CLIMB	—	1.03	0.97	0.23	0.74
				HIGH SPEED					
				CRUISE					
13 HARRISON INTERCOOLER 	ENLARGED 45 % NO FLAP	MODIFIED OUTLET 10 INCH COWL FLAP EXTEN.	DIVIDING VANE REMOVED	CLIMB	1.24	1.02	0.95	0.18	0.77
				HIGH SPEED	.98	.94	.86	.26	.60
				CRUISE	.96	.90	.84	.32	.52
14 HARRISON INTERCOOLER 	ENLARGED 45 % 12 INCH FLAP	MODIFIED OUTLET 10 INCH COWL FLAP EXTEN.	DIVIDING VANE REMOVED OIL COOLER SEALED	CLIMB	1.25	1.03	0.93	-.07	1.00
				HIGH SPEED					
				CRUISE					
15 HARRISON INTERCOOLER 	TAIL OUTLET CLOSED AND NEW OUTLET RELOCATED BEHIND COWL FLAPS	MODIFIED OUTLET 10 INCH COWL FLAP EXTEN.	DIVIDING VANE REMOVED OIL COOLER OPEN	CLIMB	1.23	1.00	0.91	0.00	0.91
				HIGH SPEED	.97	.94	.89	.40	.49
				CRUISE	.95	.92	.82	.34	.48
16 HARRISON INTERCOOLER 	TAIL OUTLET CLOSED AND NEW OUTLET RELOCATED BEHIND COWL FLAPS	MODIFIED OUTLET 10 INCH COWL FLAP EXTEN.	DIVIDING VANE REMOVED SEPARATE OIL COOLER OUTLET	CLIMB	1.20	0.95	0.87	-.15	1.02
				HIGH SPEED					
				CRUISE					
17 HARRISON INTERCOOLER 	TAIL OUTLET CLOSED AND OUTLET BEHIND COWL FLAPS ENLARGED 50 %	MODIFIED OUTLET 10 INCH COWL FLAP EXTEN.	DIVIDING VANE REMOVED SEPARATE OIL COOLER OUTLET	CLIMB	1.18	0.92	0.85	-.19	1.04
				HIGH SPEED					
				CRUISE					

TABLE IV

EFFECT OF MODIFICATIONS UPON AVERAGE TOTAL PRESSURE
THROUGHOUT THE OIL COOLER SYSTEM

Modifications				Attitude	Average total pressure at sections, H/q				
No.	Nacelle outlet	Cowling outlet	Miscellaneous		Inlet	Y	M	L	Δp/q
1	Original	Original	Airesearch intercooler	Climb High speed Cruise	1.31 .96 1.04	1.02 .83 .86	0.81 .60 .65	0.29 .24 .30	0.52 .36 .35
2	Original	Original	Intercooler nozzle removed	Climb High speed Cruise	1.34 .96 1.03	1.13 .84 .87	.88 .64 .64	.30 .30 .34	.58 .34 .30
3	Original	Original	Harrison intercooler	Climb High speed Cruise	1.32 -- --	1.16 .85 .88	.93 .65 .69	.37 .30 .36	.56 .35 .33
7	Enlarged 45% with 12-in. flap	Original		Climb	1.33	1.14	.84	.17	.67
8	Enlarged 45% with 12-in. flap	10-in. cowl flap extension		Climb	1.32	1.09	.80	.09	.71
10	Enlarged 45%, no flap	10-in. cowl flap extension		Climb	1.35	1.14	.90	.28	.62
11	Enlarged 45%, no flap	6-in. cowl flap extension		Climb	1.32	1.14	.93	.31	.62
12	Enlarged 45%, no flap	Original	Dividing vane removed	Climb	1.38	1.19	.92	.32	.60
13	Enlarged 45%, no flap	Modified outlet with 10-in. flap extension	Dividing vane removed	Climb High speed Cruise	1.36 .89 .95	1.15 .85 .86	.86 .63 .71	.28 .30 .37	.58 .33 .34
15	Outlet relocated behind cowl flaps, tail outlet closed	Modified outlet with 10-in. flap extension	Dividing vane removed	Climb High speed Cruise	-- -- --	1.16 .94 .97	.73 .72 .82	.07 .39 .45	.66 .33 .40

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TABLE V

EFFECT OF MODIFICATIONS UPON THE DRAG AND THE TOTAL PRESSURE THROUGHOUT THE OIL COOLER SYSTEM

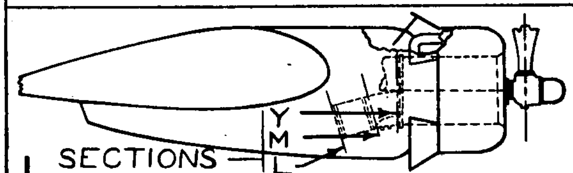
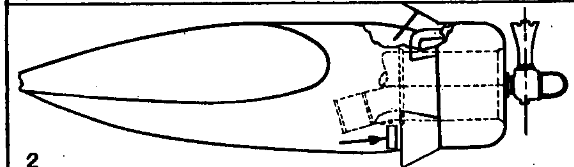
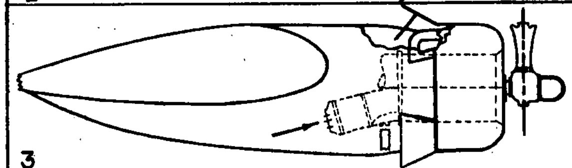
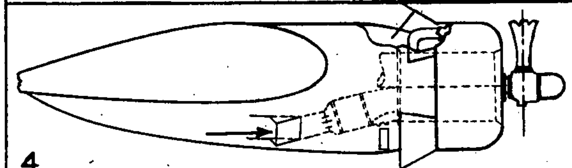
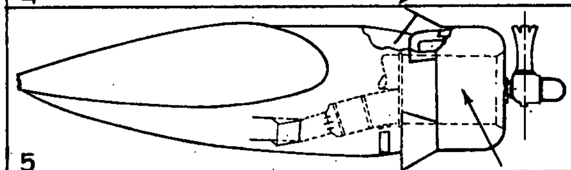
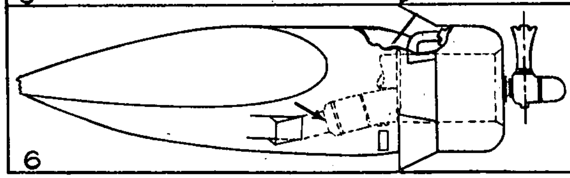
TEST CONDITION	MODIFICATIONS: OUTLET LOCATION	MODIFICATIONS: MISCELLANEOUS	ATTITUDE	AVERAGE TOTAL PRESSURE AT DUCT SECTIONS H/q_0: INLET	Y	M	L	$\Delta P/q_0$	DRAG DUE TO AIRFLOW: ΔC_{d_i}	ΔC_d
1 	ORIGINAL NACELLE TAIL OUTLET	ORIGINAL CONDITION	CLIMB HIGH SPEED	1.31 0.96	1.02 .83	0.81 .60	0.29 .24	0.52 .36	 0.0006	 0.0005
2 	RELOCATED NACELLE OUTLET		CLIMB HIGH SPEED	— —	1.16 .94	.73 .72	.07 .39	.66 .33	 .0004	 .0004
3 	RELOCATED NACELLE OUTLET	CONSOLIDATED SHUTTERS ON	CLIMB HIGH SPEED (PROP OFF)	1.42 —	1.16 .77	.98 .59	— —	.46 .32	— —	 .0004
4 	SEPARATE OIL COOLER OUTLET	SHUTTERS ON	CLIMB HIGH SPEED (PROP OFF)	1.35	1.08	.92	—	.48	—	—
5 	SEPARATE OIL COOLER OUTLET	SHUTTERS ON INLET DUCT MODIFIED AND VANES REMOVED	CLIMB HIGH SPEED (PROP OFF)	1.41 —	1.19 .69	1.11 .60	— —	.57 .30	 .0006	 .0004
6 	SEPARATE OIL COOLER OUTLET	SHUTTERS REMOVED	CLIMB HIGH SPEED (PROP OFF)	1.40 .76	1.12 .64	1.07 .52	— —	.66 .33	 .0005	 .0004

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TABLE VI

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POWER-OFF DRAG RESULTS

Test modification	Flap position	Drag coefficient		Drag increment due to modification		Drag increment referred to entire airplane		Reference figure
		C_D at $C_L = 0.18$	C_D at $C_L = 0.60$	ΔC_D at $C_L = 0.18$	ΔC_D at $C_L = 0.60$	ΔC_D at $C_L = 0.18$	ΔC_D at $C_L = 0.60$	
(a) Flap Modification								
1 Wing alone	Closed	0.0128	------	------	------	------	------	--
2 Nacelle completely faired	--do--	.0163	0.0532	0.0035	------	0.0064	------	83
3 Supercharger and shroud unsealed	--do--	.0185	------	.0022	------	.0040	------	85
4 Duct inlets and outlets opened	--do--	.0196	------	.0011	------	.0020	------	--
5 Engine air inlet and outlet opened	--do--	.0212	.0610	.0016	------	.0029	------	4
6 Modified cowl outlet and cowl flaps extended 10 inches	--do--	.0210	.0603	-.0002	------	-.0004	------	37
7 Engine air inlet and outlet opened	Open	------	.0725	------	------	------	------	4
8 Modified cowl outlet	-do-	------	.0734	------	0.0009	------	0.0016	36
9 Cowl flap extended 6 inches	-do-	------	.0790	------	.0056	------	.0102	37
10 Modified cowl outlet with cowl flaps extended 10 inches	-do-	------	.0910	------	.0176	------	.0320	41
11 Nacelle outlet flap added	-do-	------	.0935	------	.0025	------	.0045	--
12 Nacelle outlet flap added	Closed	.0215	------	.0005	------	.0008	------	--
(b) Oil-Cooler Modification								
13 Original condition; oil cooler and intercooler unsealed; duct inlets and outlets opened	Closed	0.0196	------	0.0011	------	0.0020	------	--
14 Modified base; relocated nacelle outlet; intercooler and oil cooler sealed	--do--	.0204	------	------	------	------	------	--
15 Relocated nacelle outlet with intercooler and oil cooler unsealed	--do--	.0213	0.0618	.0009	------	.0016	------	70
16 Relocated nacelle outlet with intercooler and oil cooler unsealed, with oil-cooler shutter installed	--do--	.0213	.0620	0	-0.0002	0	0.0004	80
17 Relocated nacelle outlet with intercooler and oil cooler unsealed, with oil-cooler shutter installed, with separate oil-cooler outlet	--do--	.0212	.0620	-.0001	0	-.0002	0	81
18 Relocated nacelle outlet with intercooler and oil cooler unsealed, with separate oil-cooler outlet	--do--	.0212	.0618	-.0001	0	-.0002	0	81
19 Relocated nacelle outlet with oil cooler unsealed, with separate oil-cooler outlet, with intercooler sealed	--do--	.0208	.0610	-.0004	-.0008	-.0007	-.0015	--
20 Relocated nacelle outlet with separate oil-cooler outlet sealed and with intercooler sealed	--do--	.0204	------	-.0004	------	-.0007	------	--
(c) Supercharger Modification								
21 Nacelle completely faired	Closed	0.0163	------	------	------	------	------	83
22 Supercharger and shroud unsealed	--do--	.0185	------	0.0022	------	0.0040	------	85
23 Reference base for follo ing modifications:	--do--	.0213	.0618	------	------	------	------	--
24 Turbo hood added	--do--	.0214	.0620	.0001	.0002	.0002	.0004	87
25 New nacelle afterbody added	--do--	.0233	.0626	.0019	.0006	.0035	.0011	88
26 Sealed leaks in nacelle afterbody	--do--	.0206	.0617	-.0026	-.0009	-.0046	-.0016	89

TABLE VII

NATIONAL ADVISORY
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POWER-ON DRAG RESULTS

Test modification	Lift coefficient of model [3] C_L	[1] Drag coefficient of model C_D at C_L=0.7	Increment in drag coefficient due to modification: ΔC_D (referred to tunnel model)	Increment in drag coefficient due to modification: ΔC_D (referred to entire airplane)	Increment in internal drag due to modification [4] ΔC_{D_i} (referred to entire airplane)	[2] Change in rate of climb at 25,000 ft ΔC_h (ft/min)
I. Original condition, cowl flap closed	0.733	-0.0231	------	------	------	----
II. Original condition, cowl flap open	.721	-.0109	0.0122	0.0222	0.0043	----
A. Oil cooler sealed	.719	-.0107	.0002	.0004	------	----
1. Enlarged nacelle outlet	.719	-.0096	.0011	.0020	------	-50
2. Enlarged nacelle outlet and 12-inch nacelle flap	.718	-.0079	.0028	.0051	------	-125
B. Enlarged nacelle outlet and 12-inch flap	.721	-.0082	.0027	.0049	------	-120
1. 10-inch cowl-flap extension	.695	.0058	.0140	.0255	.0017	-610
2. 10-inch cowl-flap extension with push-rod holes sealed	.697	.0060	.0142	.0259	------	-620
C. Enlarged nacelle outlet	-----	-.0098 (est.)	------	------	------	----
1. 10-inch cowl-flap extension	.698	.0039	.0137	.0250	------	-600
2. 6-inch cowl-flap extension	.715	-.0035	.0065	.0115	.0010	-280
3. Intercooler vane removed	.720	-.0095	.0003	.0005	------	----
4. Intercooler vane removed and with revised cowl outlet	.720	-.0077	.0021	.0038	.0008	-95
(a) 6-inch cowl-flap extension	.713	-.0018	.0059	.0107	.0011	-255
(b) 10-inch cowl-flap extension	.691	.0064	.0141	.0257	.0018	-615
(1) Oil cooler sealed and nacelle flap on	.686	.0068	.0004	.0007	------	----
(2) Flap ends sealed	.713	.0018	-.0046	-.0084	------	200
III. Original condition, cowl flap open, with 10-inch flap extension, modified cowl outlet, and no intercooler vane	.691	.0064	------	------	------	----
A. Spinner blower at 48°	.686	.0084	.0020	.0036	.0014	-90
B. Spinner blower at 58°	.686	.0117	.0053	.0096	.0021	-230
C. Spinner blower at 58° with relocated nacelle outlet	.686	.0112	.0048	.0087	------	-210
D. Dishpan blower at 58° with relocated nacelle outlet	.684	.0102	.0038	.0069	.0024	-170
1. Guide vanes	.686	.0109	.0007	.0013	------	----
2. Flaps closed	-----	-.0085	-.0187	-.0340	------	----
IV. Modified base, 10-inch flap extension and modified cowl outlet; relocated nacelle outlet; oil-cooler shutters	.679	.0124	------	------	------	----
A. Separate oil-cooler outlet with oil-cooler flap closed	.679	.0115	-.0009	-.0016	------	----
B. Separate oil-cooler outlet with oil-cooler flap open	.677	.0140	.0016	.0029	------	----
1. Refaired duct	.675	.0143	.0003	.0005	------	----
2. Refaired duct and shutters removed	.680	.0136	-.0004	-.0007	------	----

[1] Drag coefficient corrected to $V/nD = 0.754$ and $C_L = 0.70$.

[2] Based on an indicated climbing speed of 150 miles per hour; flaps deflected 30°.

[3] Constant tunnel angle.

[4] $C_{D_i} = \frac{Q\Delta p}{qSV}$ where Q = quantity of cooling-air flow, Δp = engine pressure drop, q = test dynamic pressure, S = wing area, V = test velocity.

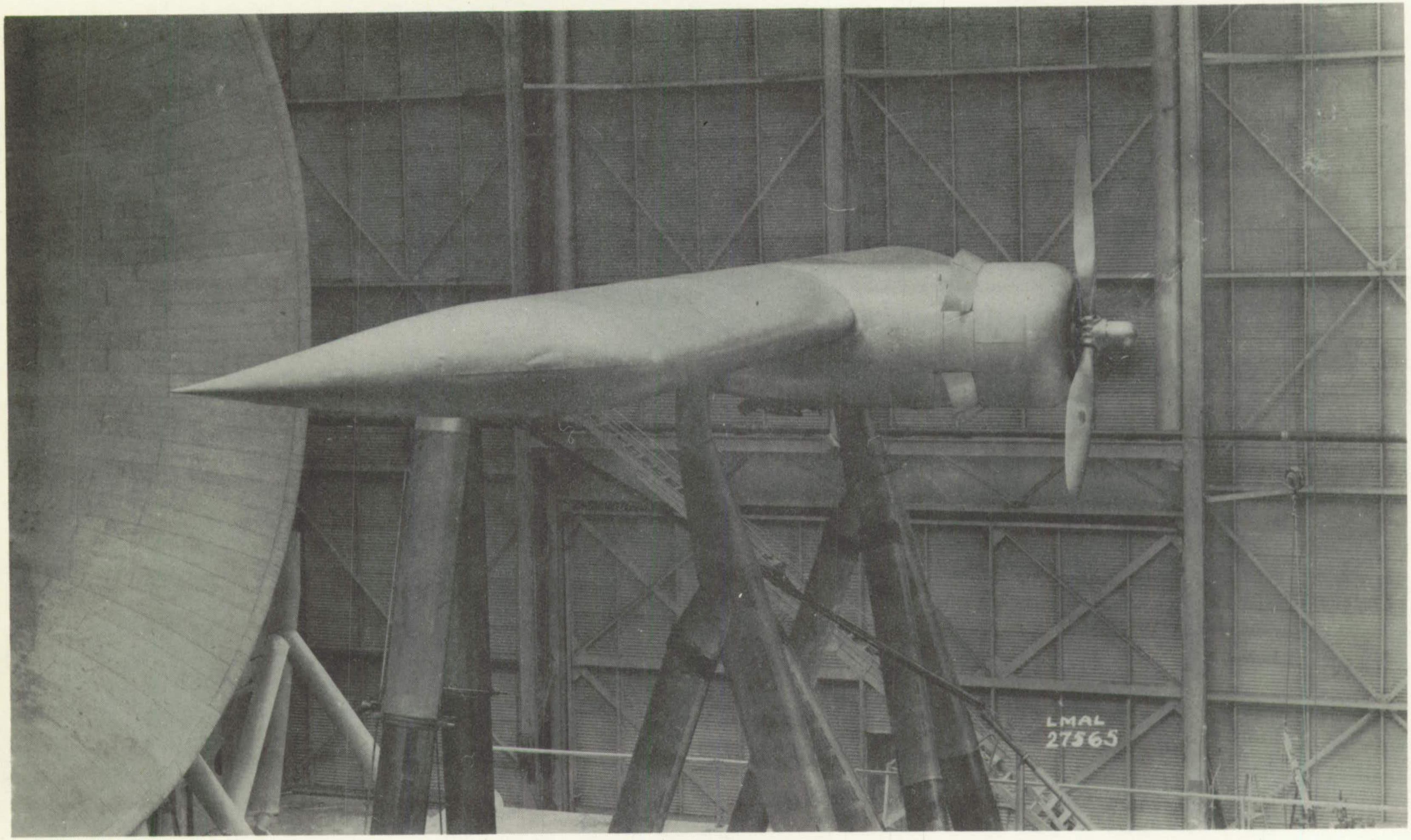

Figure 1.- Original B-24D wing-nacelle installation in the full-scale wind tunnel.

1. Total-pressure tubes at all shaded sections.
2. Static-pressure tubes at sections K and W.
3. Thermocouples at sections A,C,D,E,S, and at outlet of supercharger.

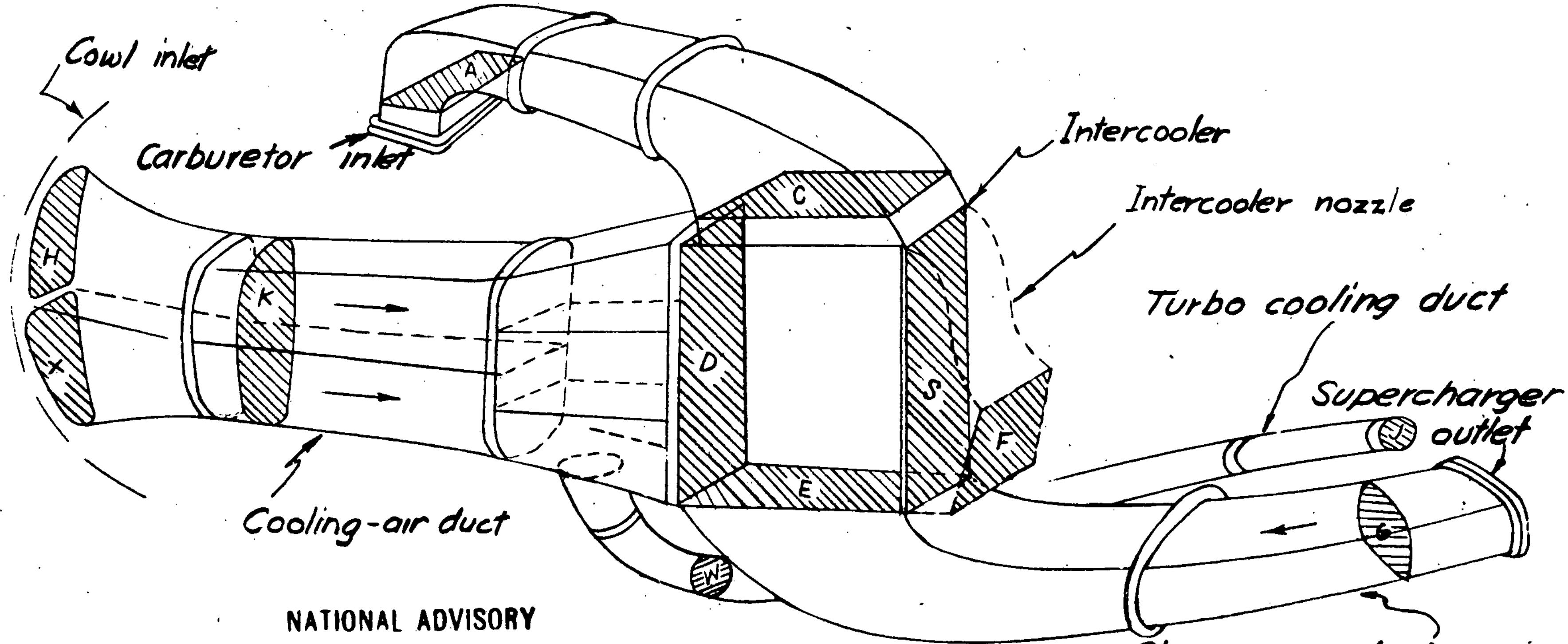

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Figure 2.- B-24D intercooling system.

1. Total-pressure tubes at all shaded sections
2. Static-pressure tubes at sections Y
3. Thermocouples at section M and at inlet to supercharger

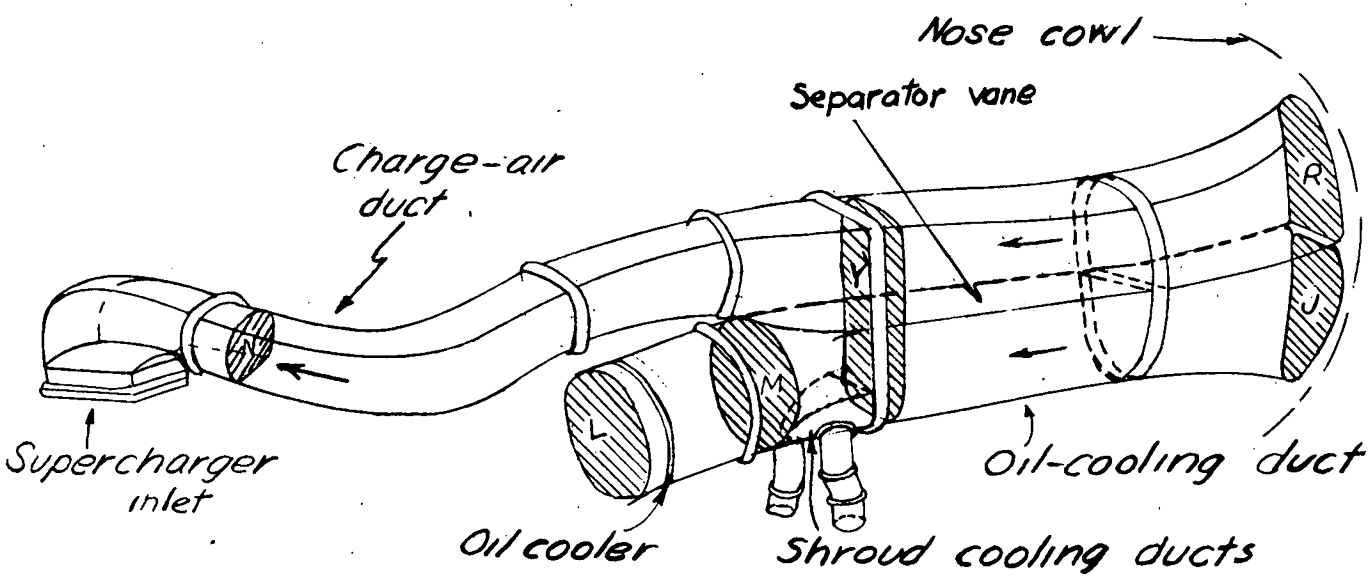

Figure 3.- B-24D charge-air duct from cowl inlet to supercharger and oil-cooling duct.

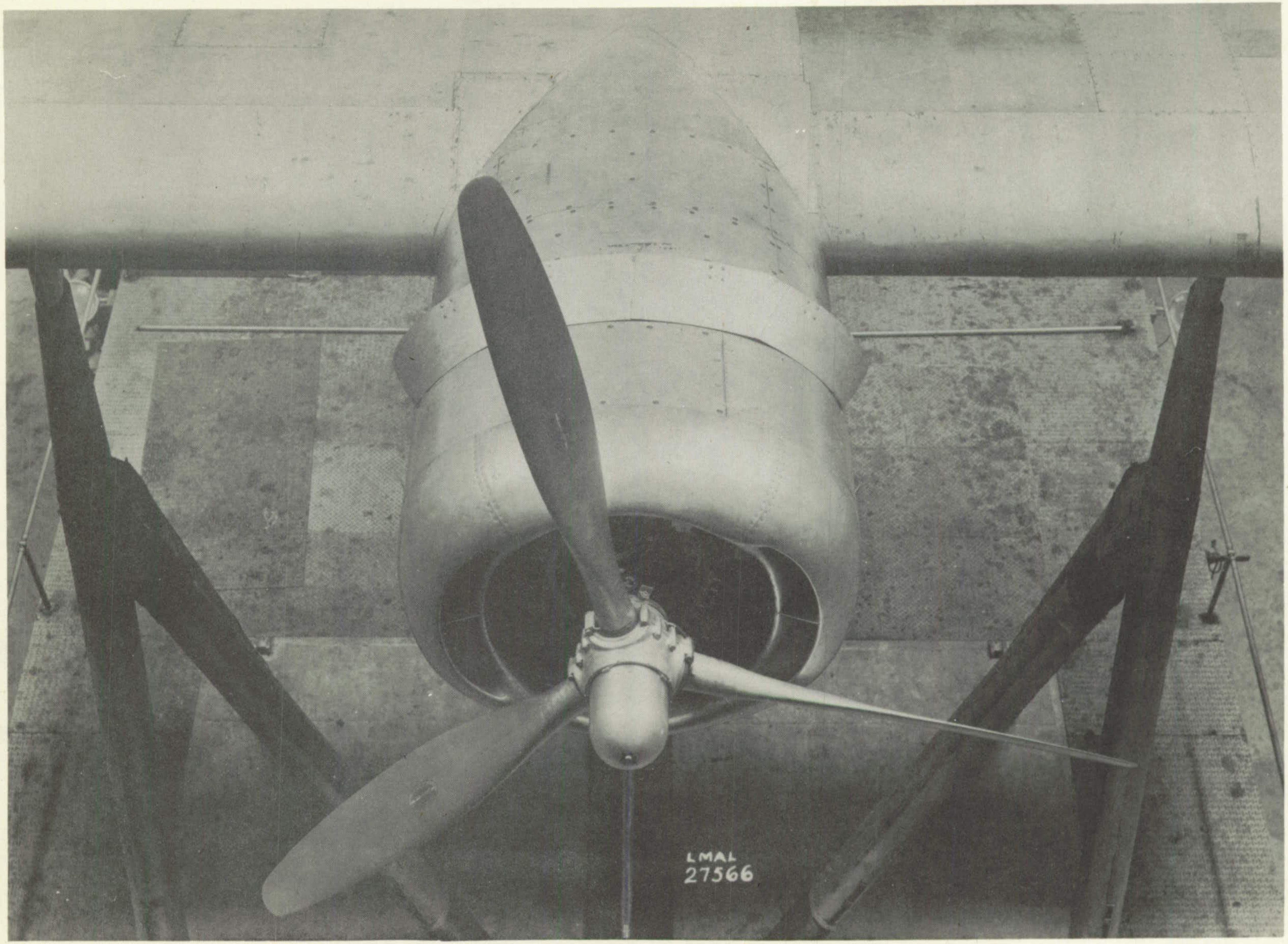

Figure 4.- Duct inlets on the B-24D engine-nacelle installation.

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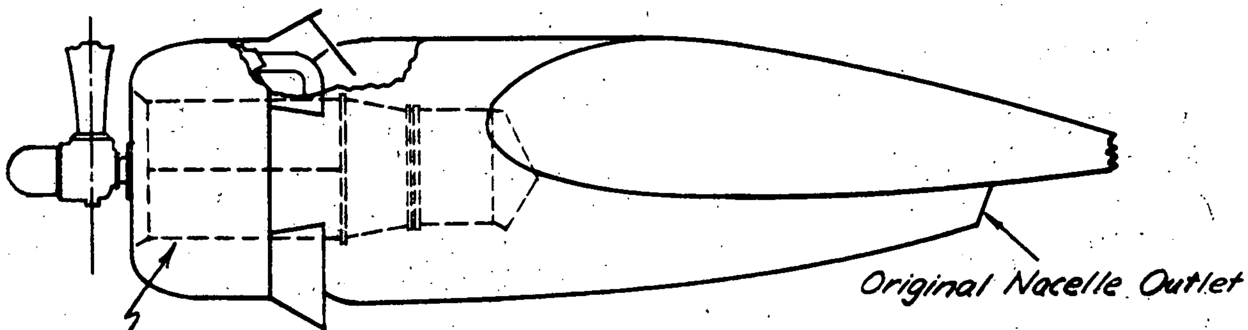
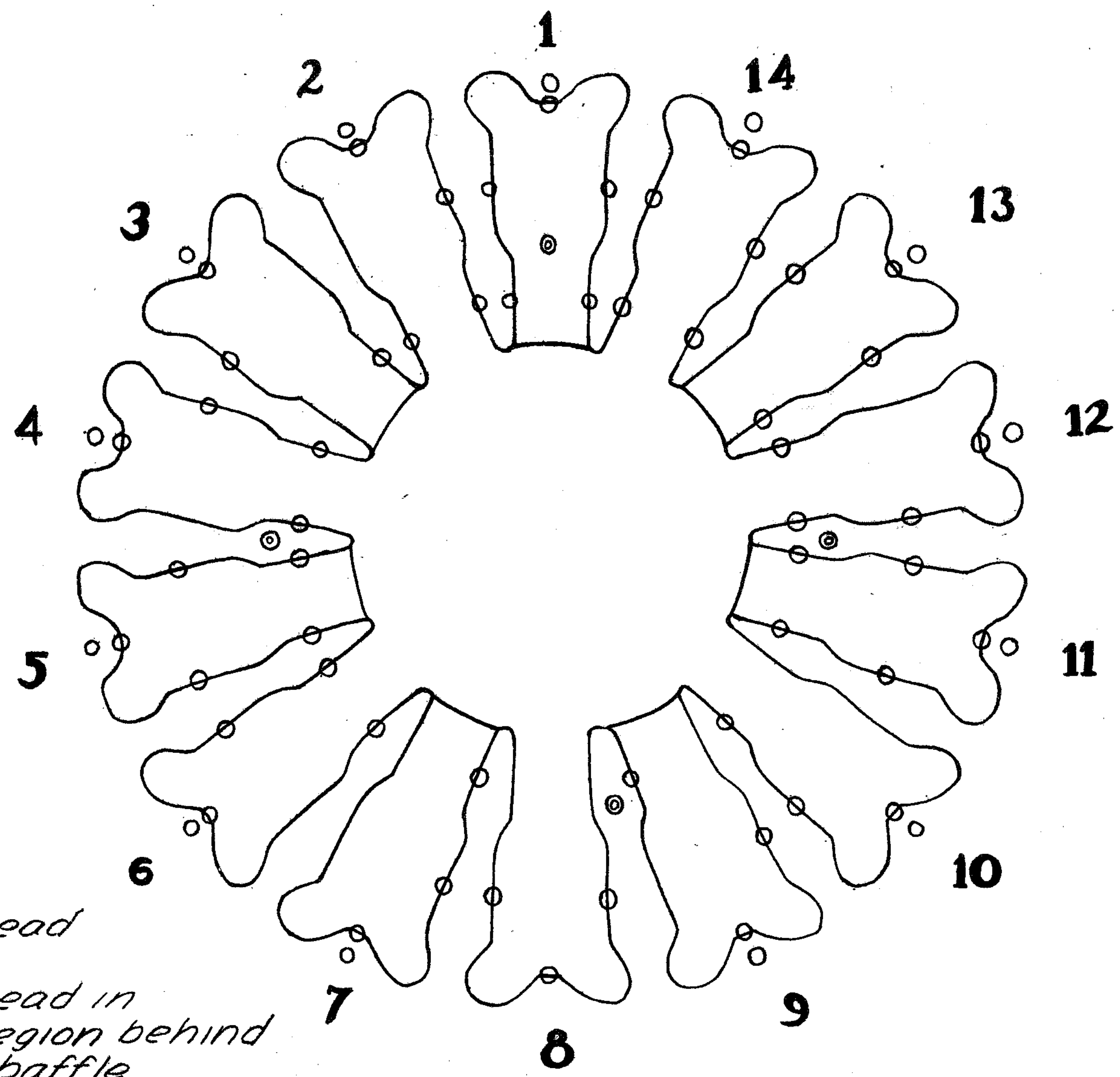


FIGURE 5.- SIDE VIEW OF THE ORIGINAL B-24 D ENGINE-NACELLE INSTALLATION.



FRONT VIEW

o Total head
⊗ Static
● Total head in dead region behind head baffle
◎ Shielded total head

Thermocouples at head and base of each culinder

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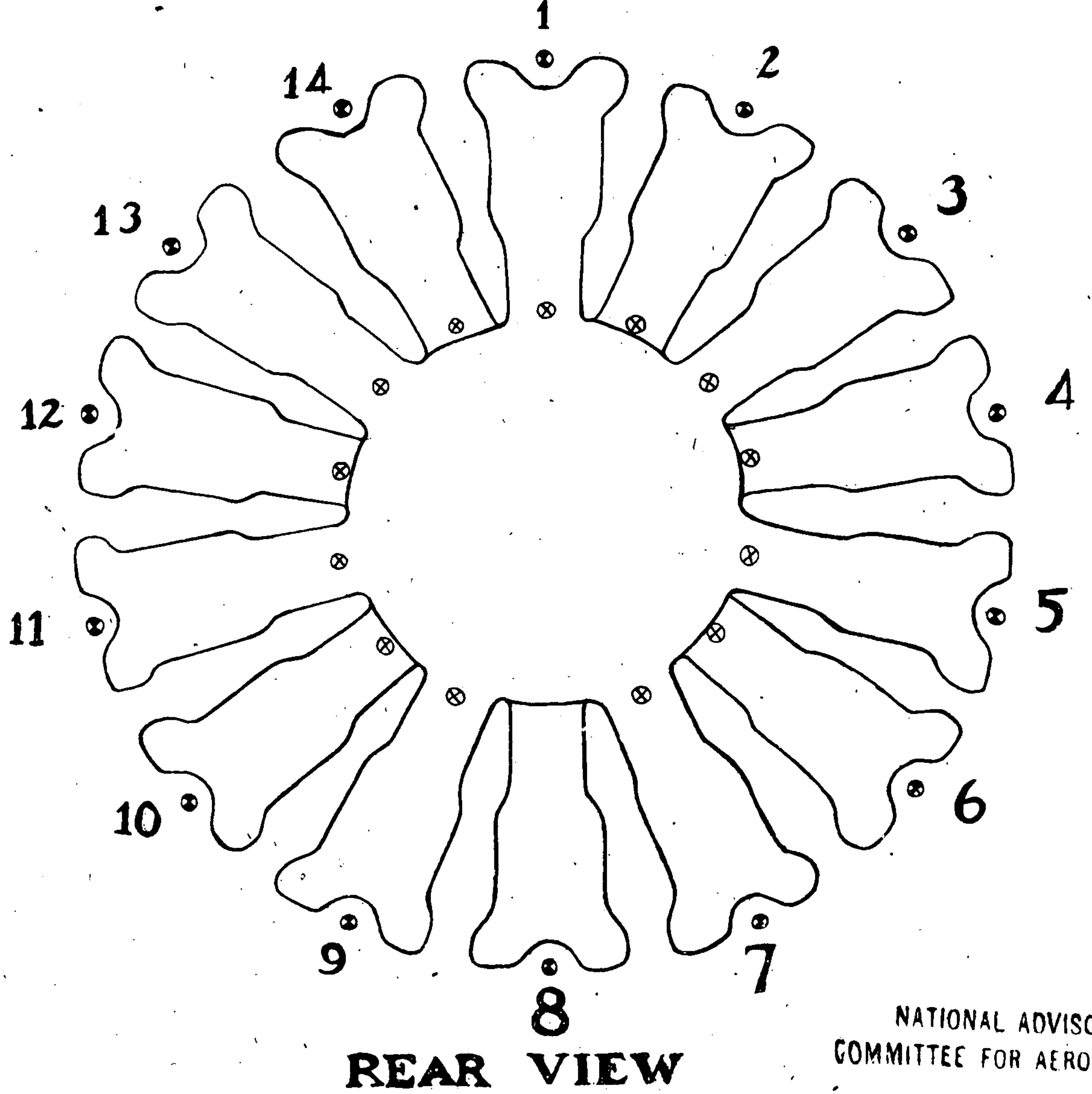

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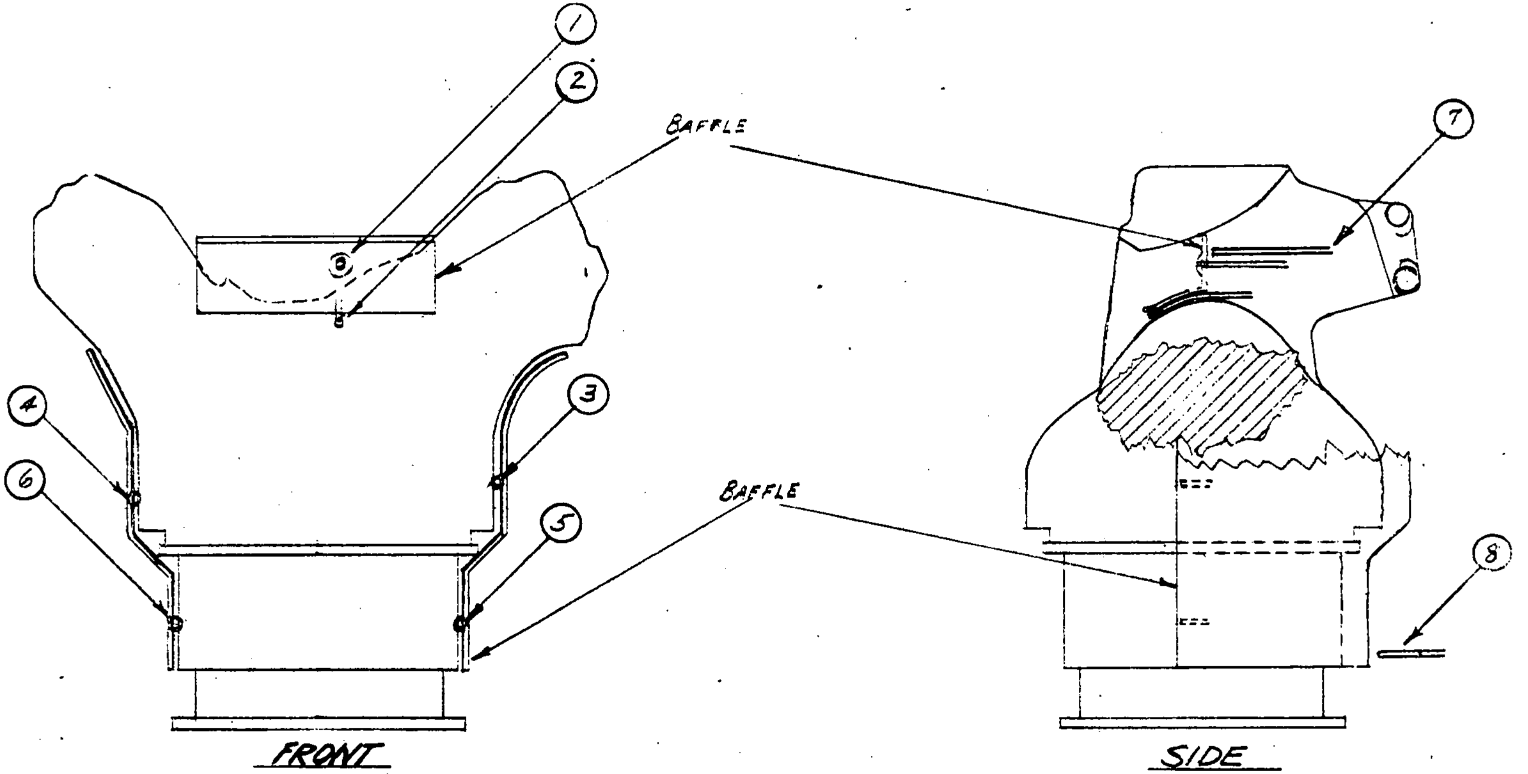
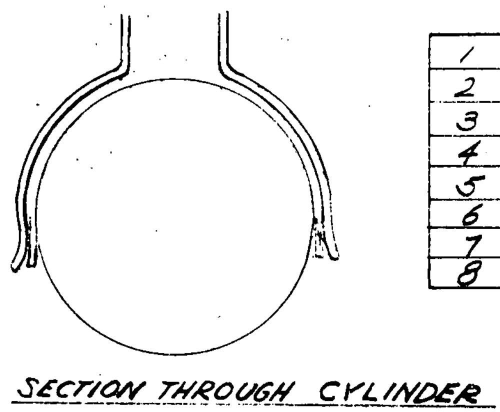
Figure 6.— Engine pressure-tube locations on the B-24D engine installation.





	READING	LOCATION
1	TOTAL PRESSURE	BUTTON IN HEAD BAFFLE
2	TOTAL PRESSURE	BETW. FINS 9&10 (FROM INTAKE)
3	TOTAL PRESSURE	BETW. FINS 7&8
4	TOTAL PRESSURE	BETW. FINS 5&6
5	TOTAL PRESSURE	BETW. FINS 8&9
6	TOTAL PRESSURE	BETW. FINS 8&9
7	STATIC PRESSURE	1/4" FROM BAFFLE
8	STATIC PRESSURE	OPP. 4TH FIN FROM BOTTOM

NOT TO SCALE

Figure 7. - Location of tubes for measuring the front and rear cylinder pressures on the B-24D engine installation.

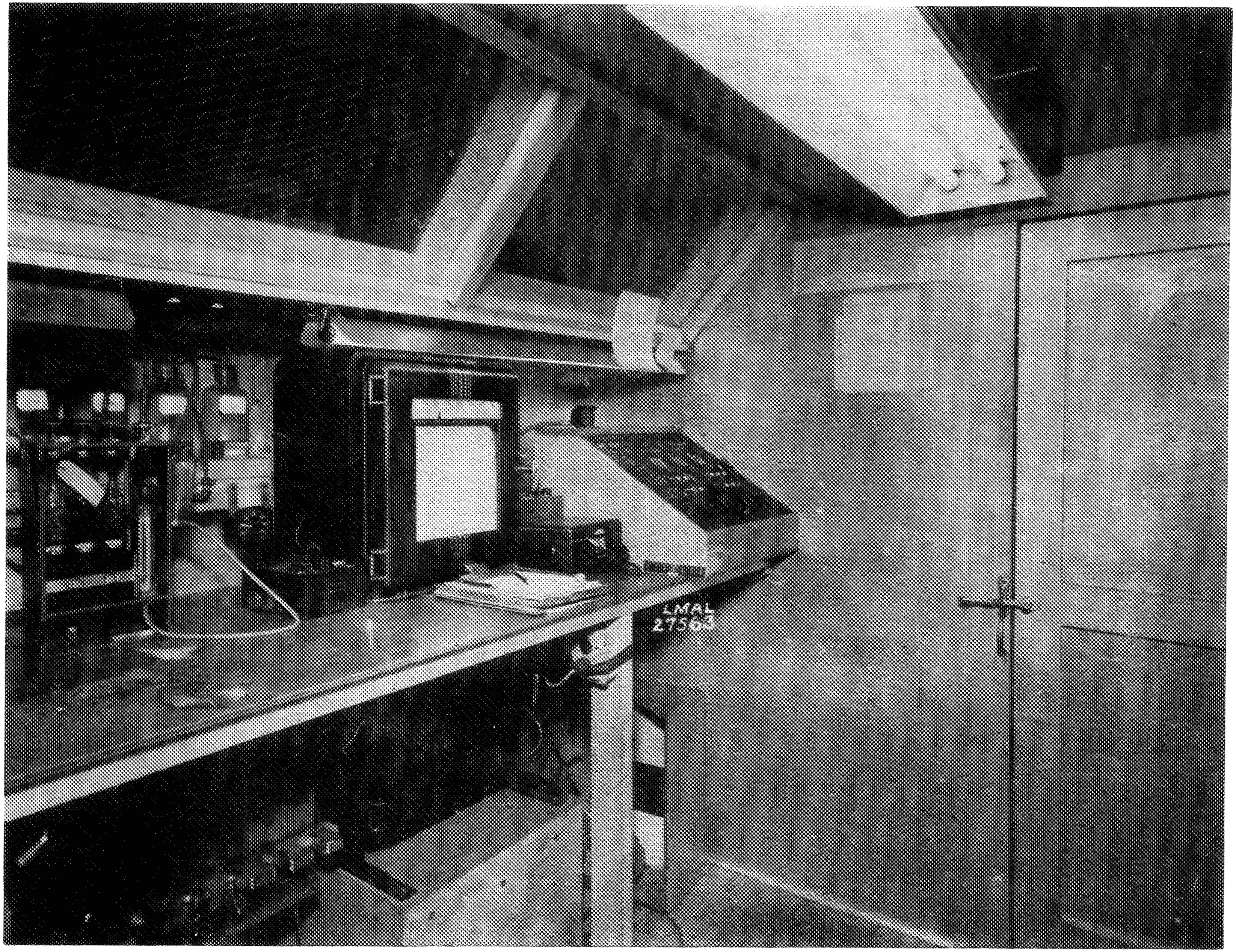


Figure 8.- View of test house showing engine-control panel, temperature recorder, and Orsat analyzer used in the B-24D tests.

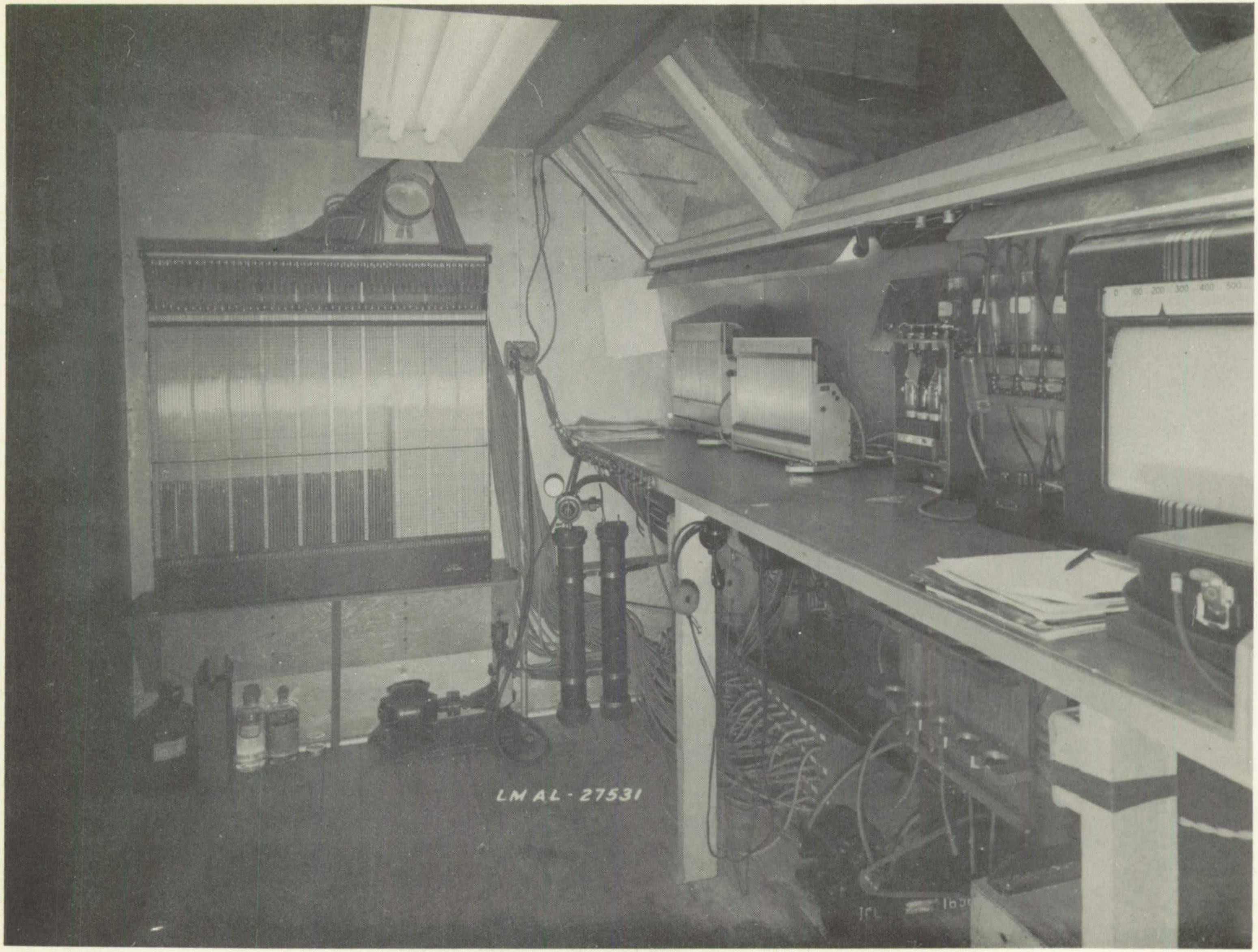
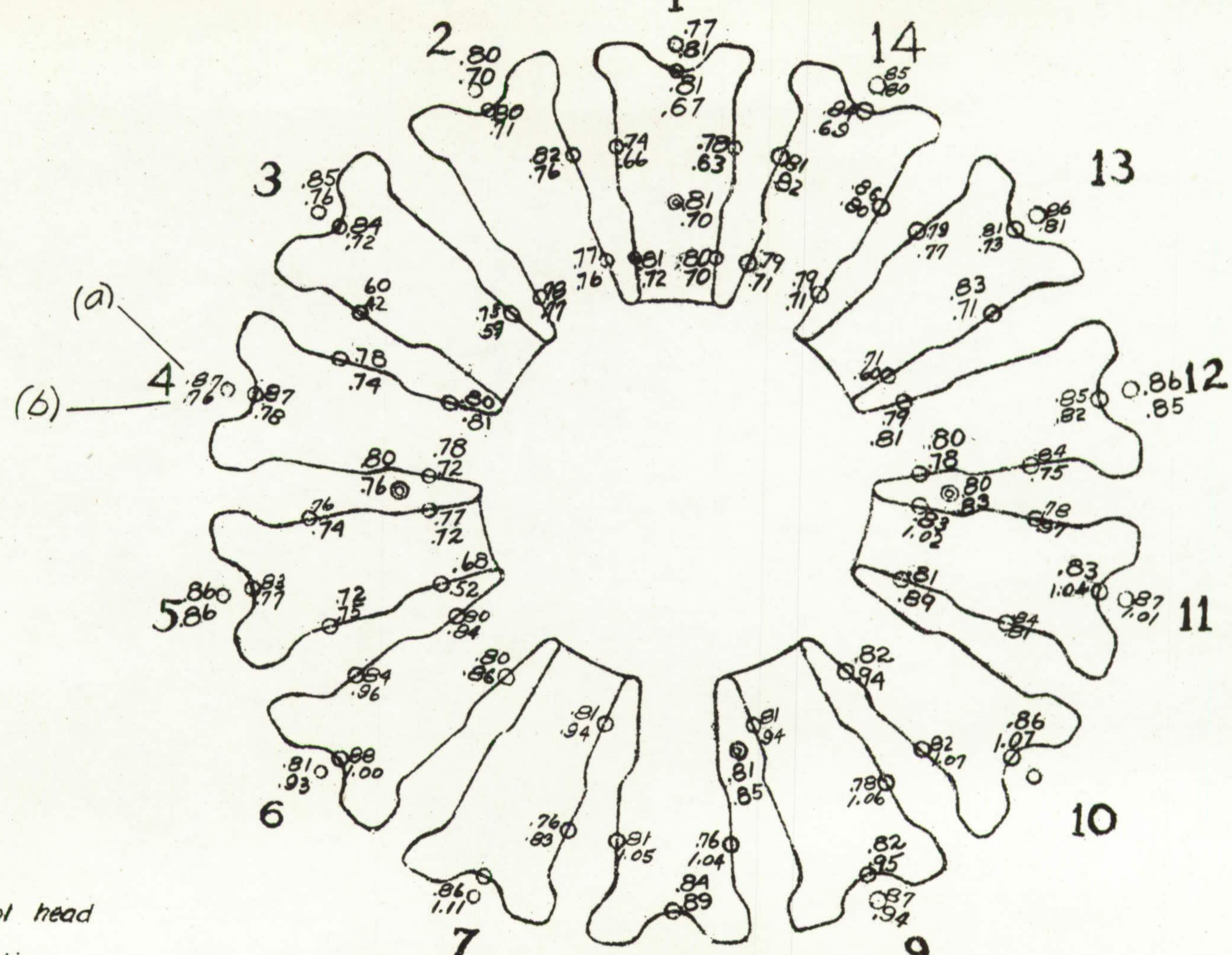


Figure 9.- View of test house showing the manometers used in the B-24D tests.



○ Total head

⊗ Static

● Total head in dead region behind head baffle

◎ Shielded total head

FRONT VIEW

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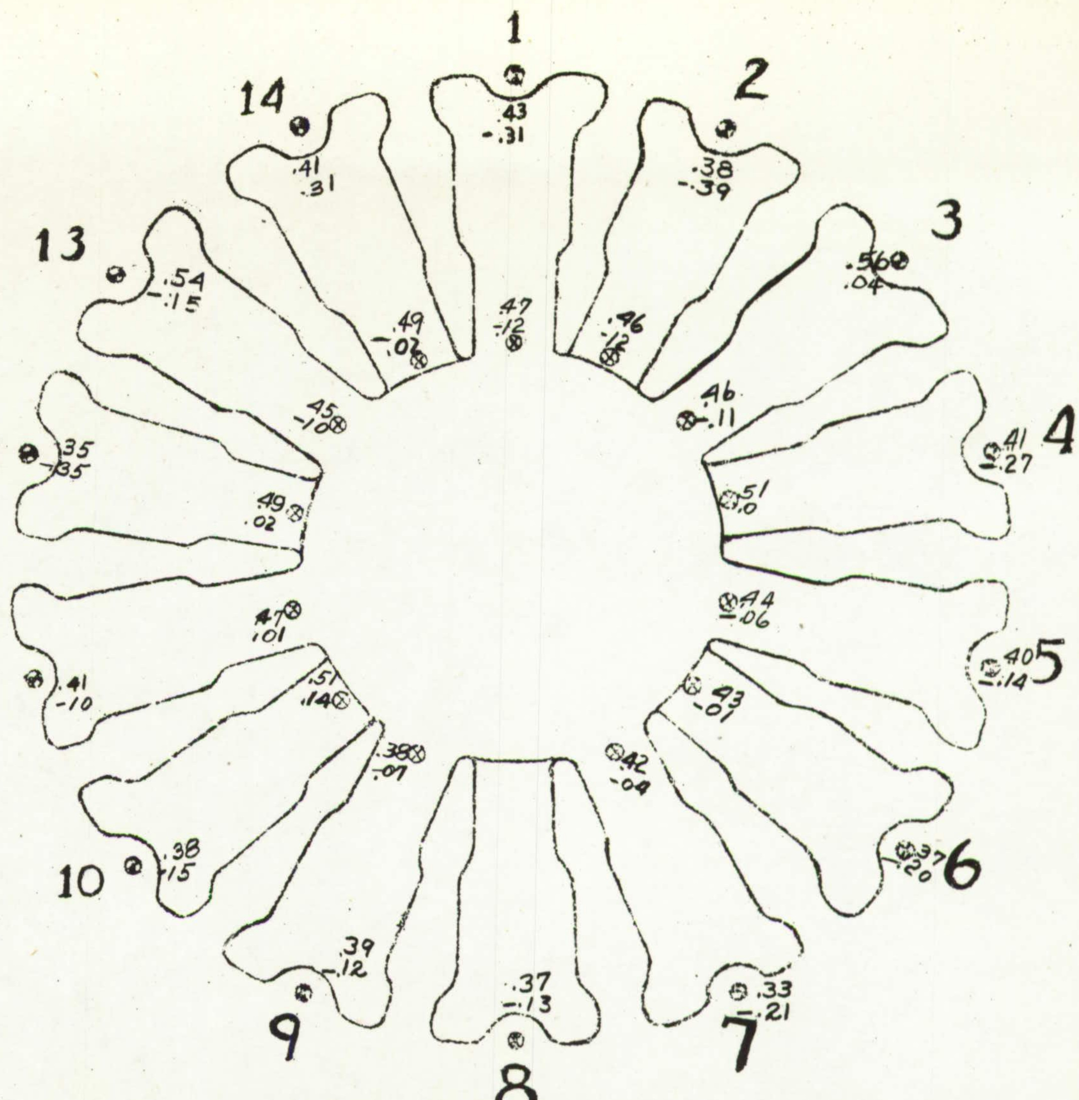

(a) High speed

(b) Climb

REAR VIEW

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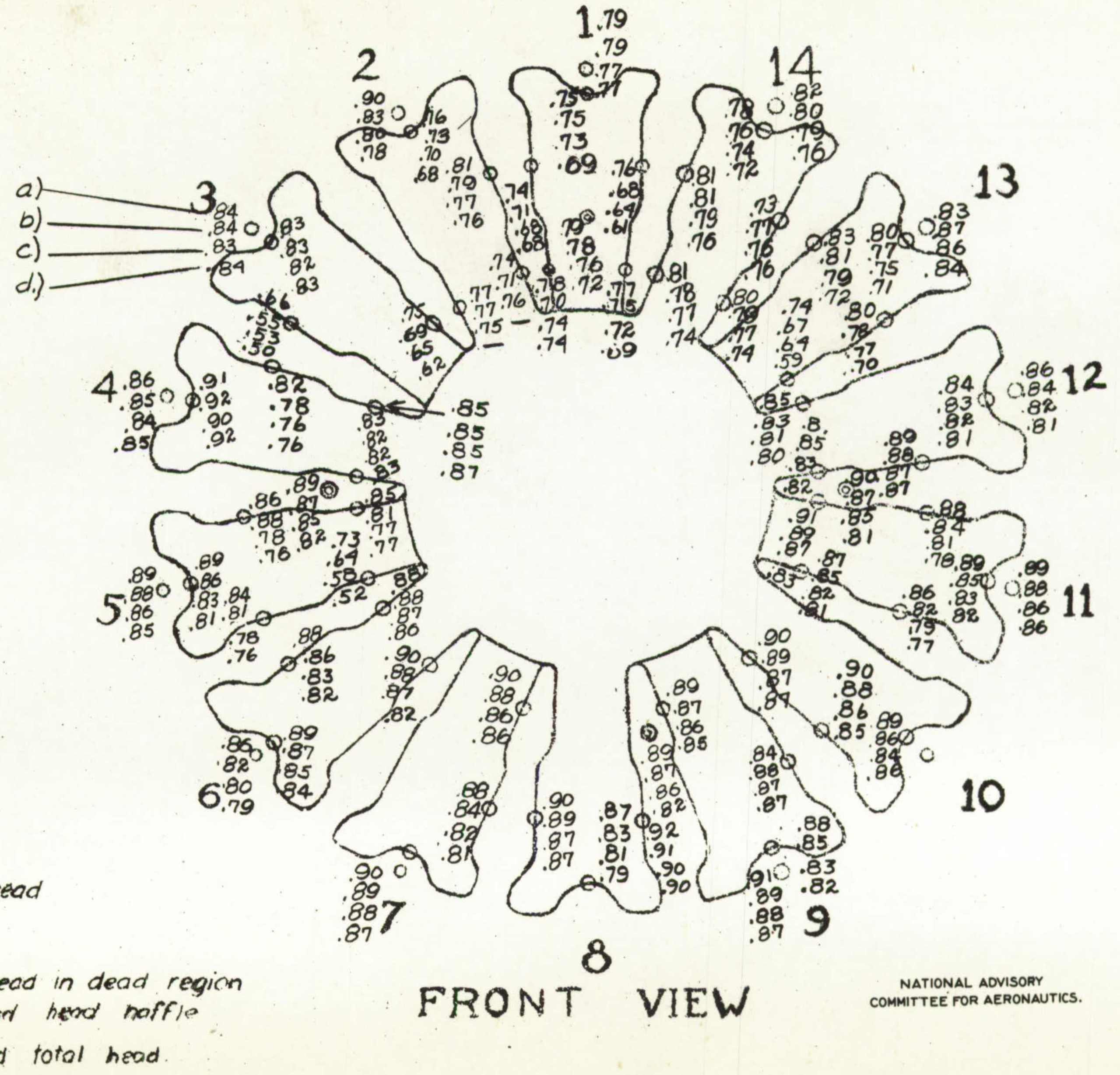
FIGURE 10. - ENGINE PRESSURE DISTRIBUTION FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION IN HIGH SPEED AND CLIMB.



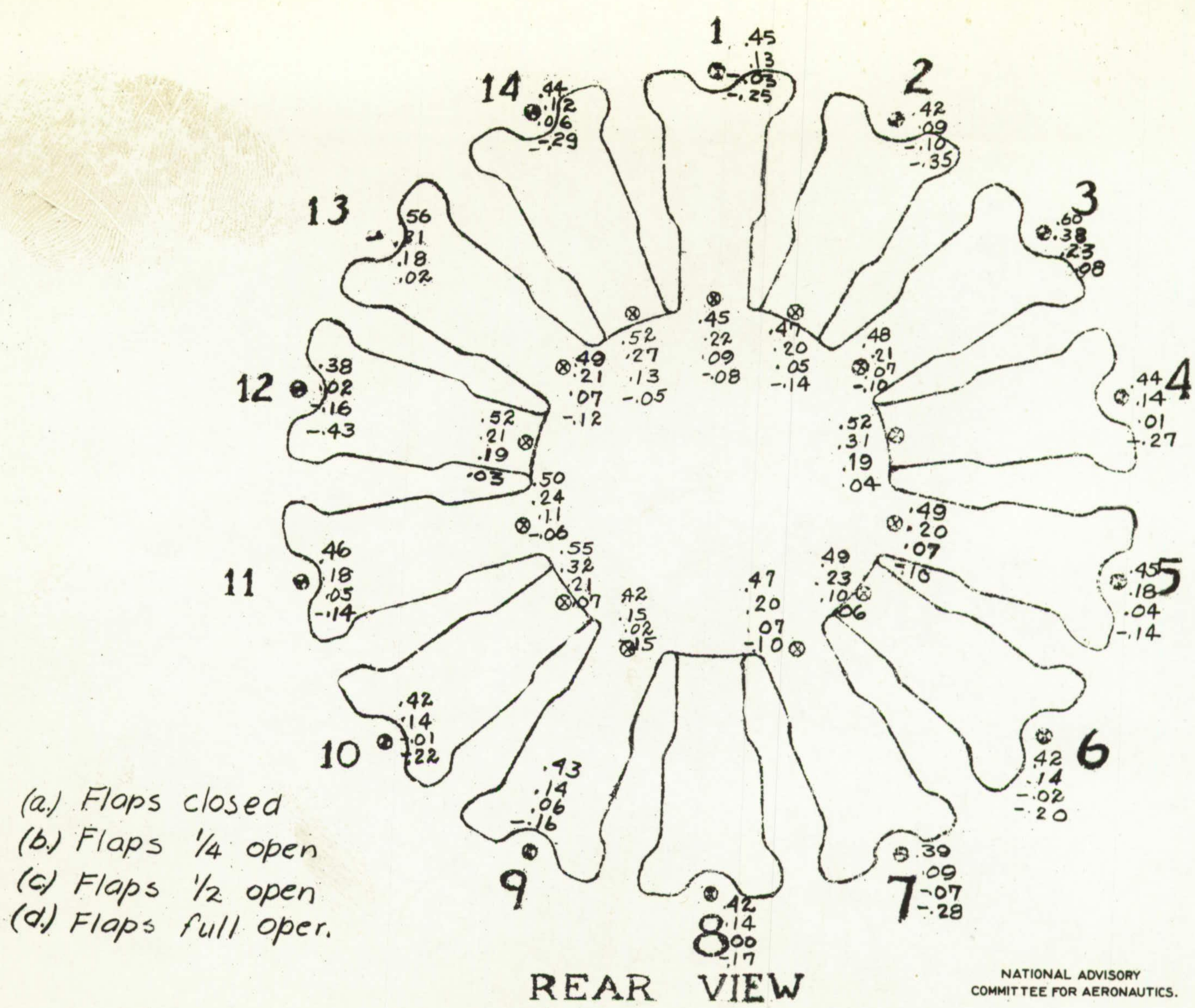


FIGURE 11. - ENGINE PRESSURE DISTRIBUTION FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION IN CRUISING.

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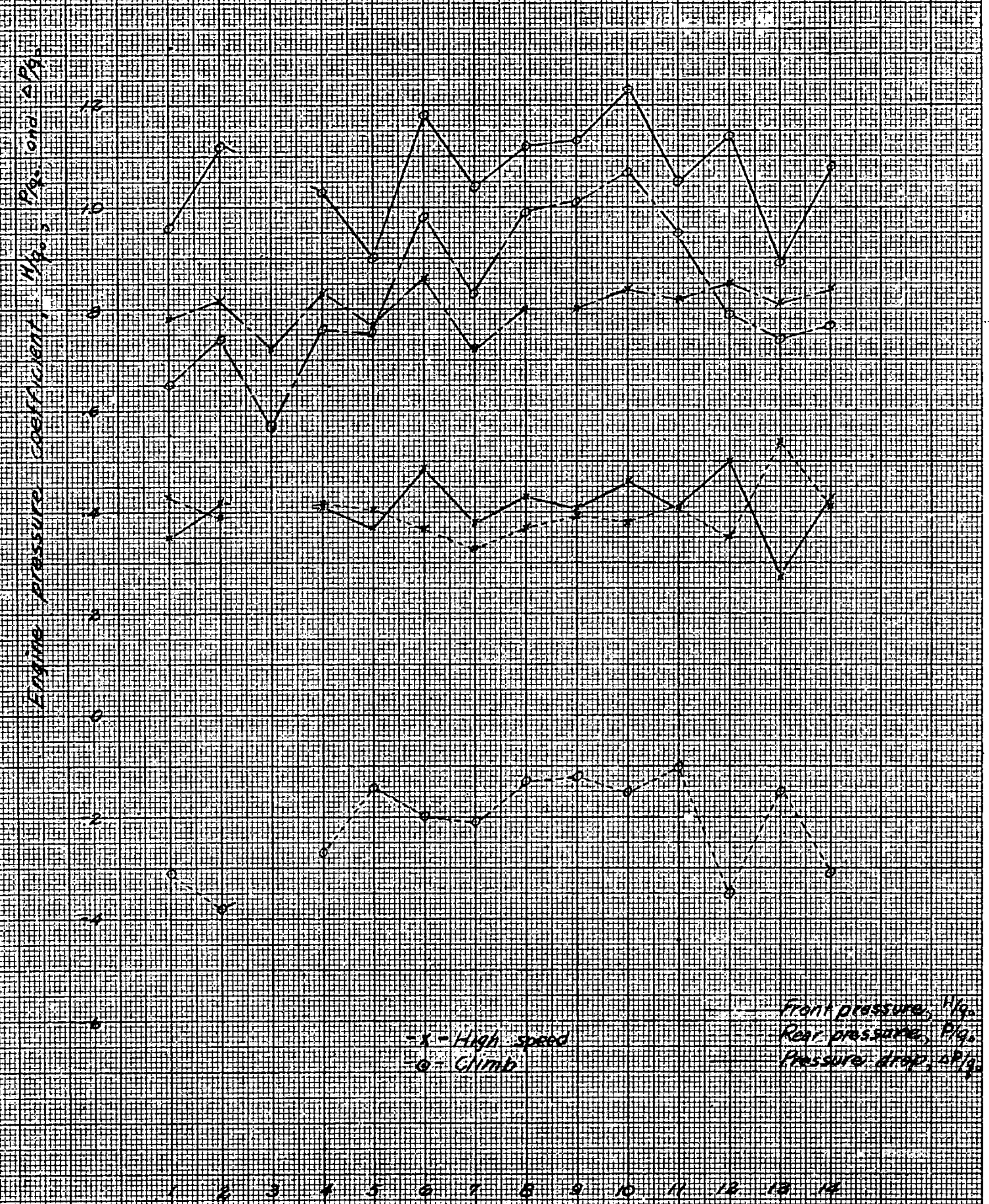

Figure 12. - Variation of the front and rear head pressures and the corresponding pressure drop for high-speed and climb attitudes; original condition.

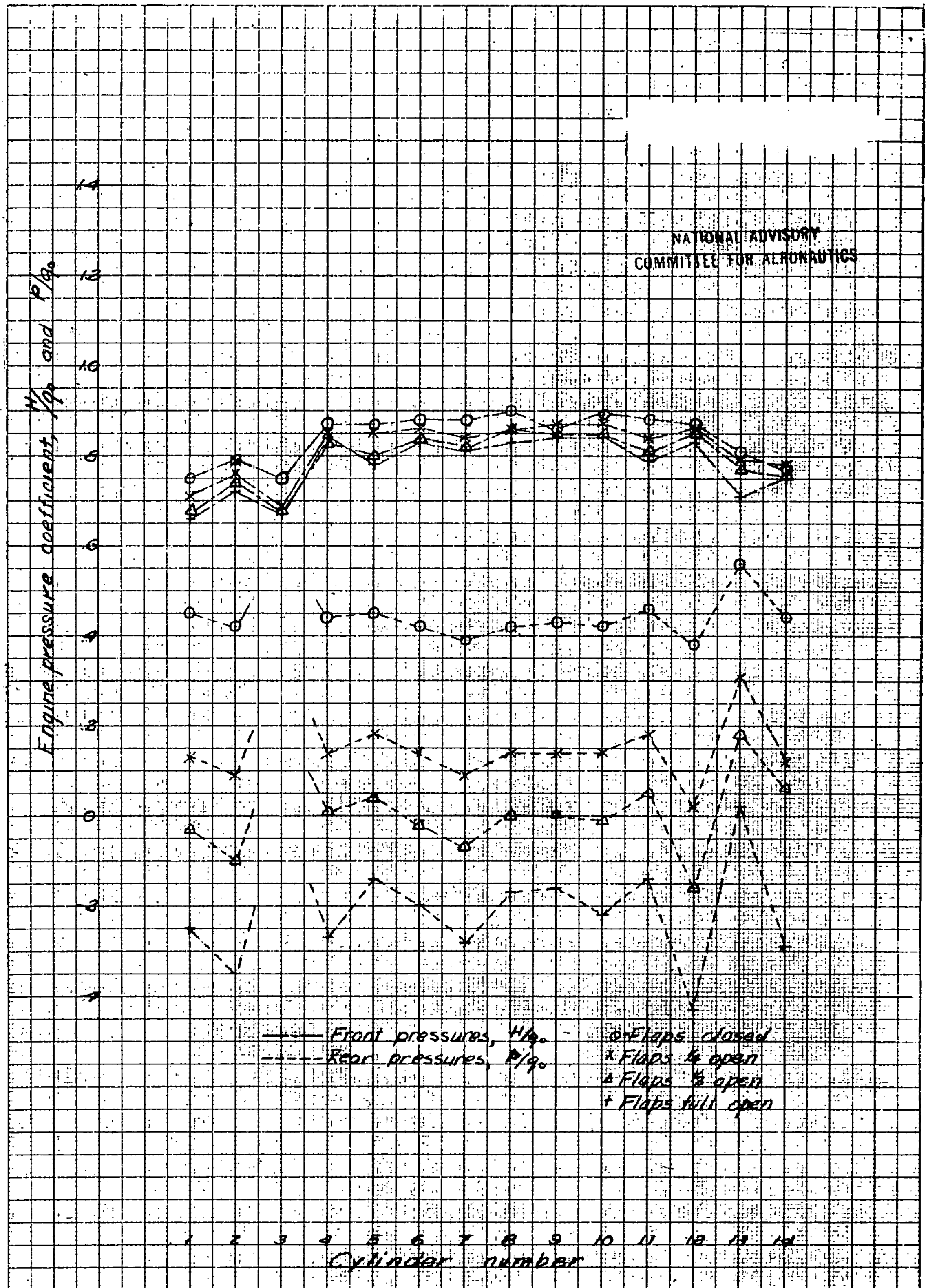

Figure 13. - Variation of the front and rear head pressures with flap angle for the cruising attitude; original condition.

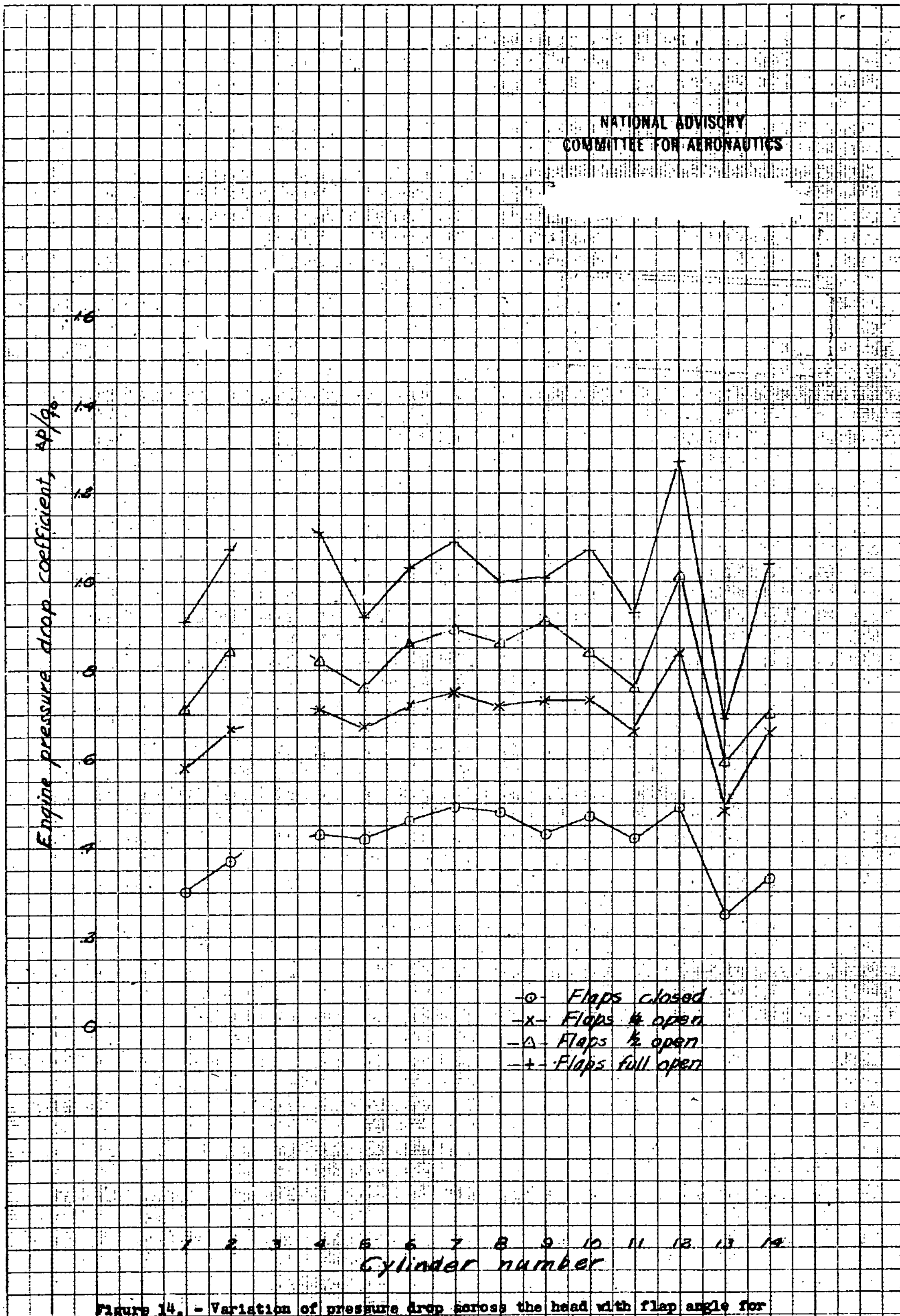

Figure 14. - Variation of pressure drop across the head with flap angle for the cruising attitude; original condition.

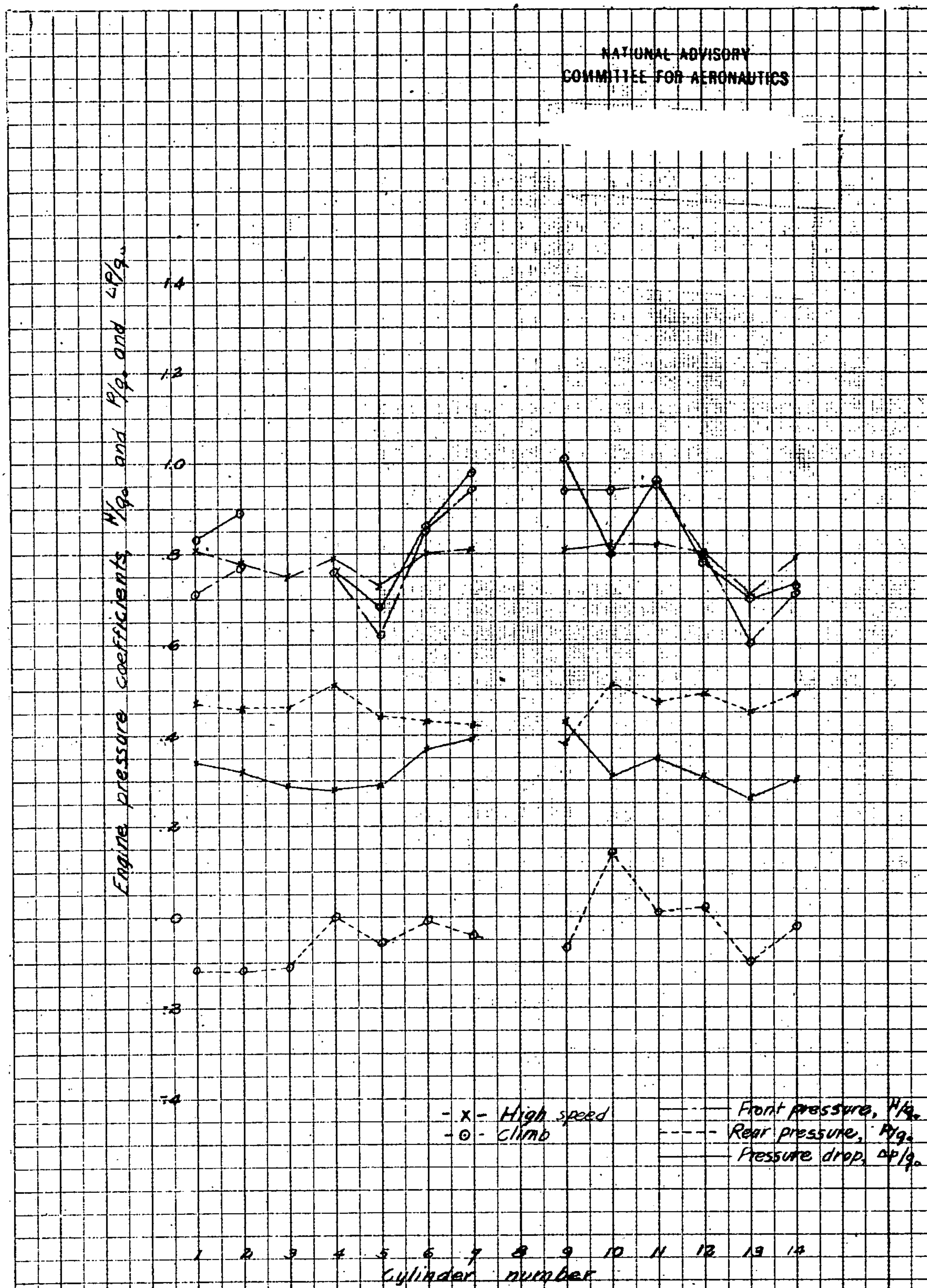

Figure 15. - Variation of the front and rear barrel pressures and the corresponding pressure drop for the high-speed and climb attitudes; original condition.

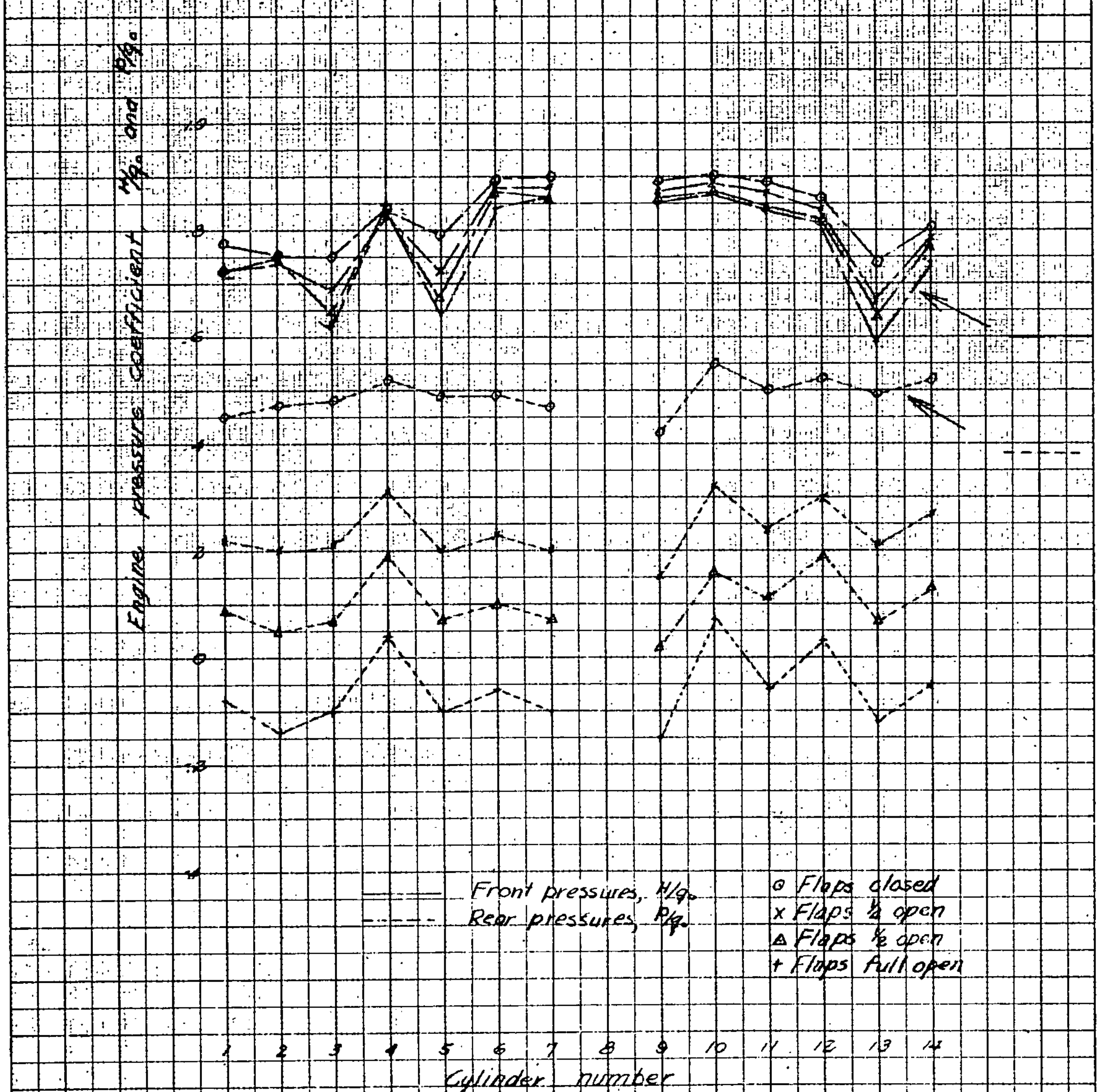

Figure 16. - Variation of the front and rear barrel pressures with flap angle for cruising attitude; original condition.

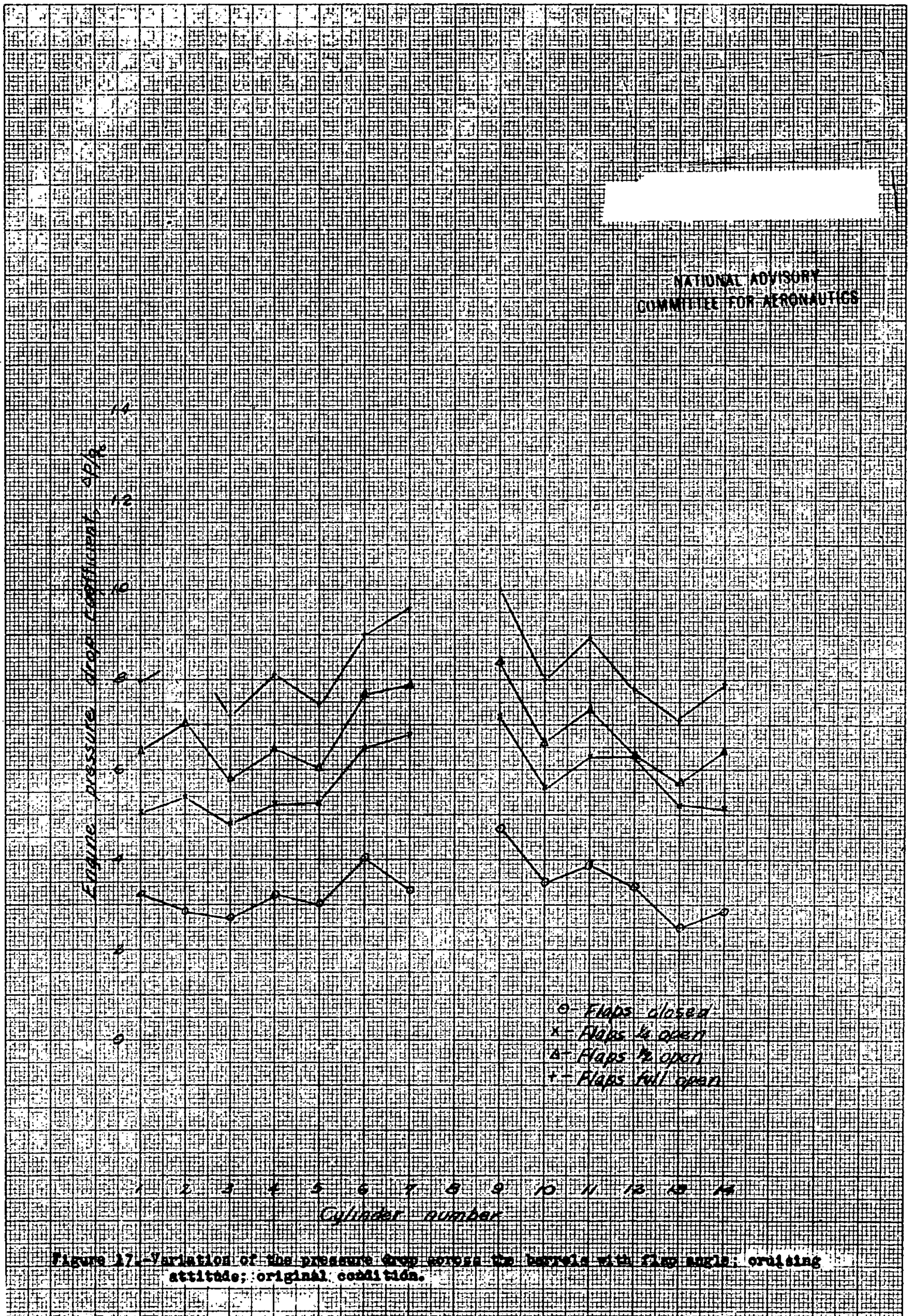

Figure 17.-Variation of the pressure drop across the barrels with flap angle; cruising attitude; original condition.

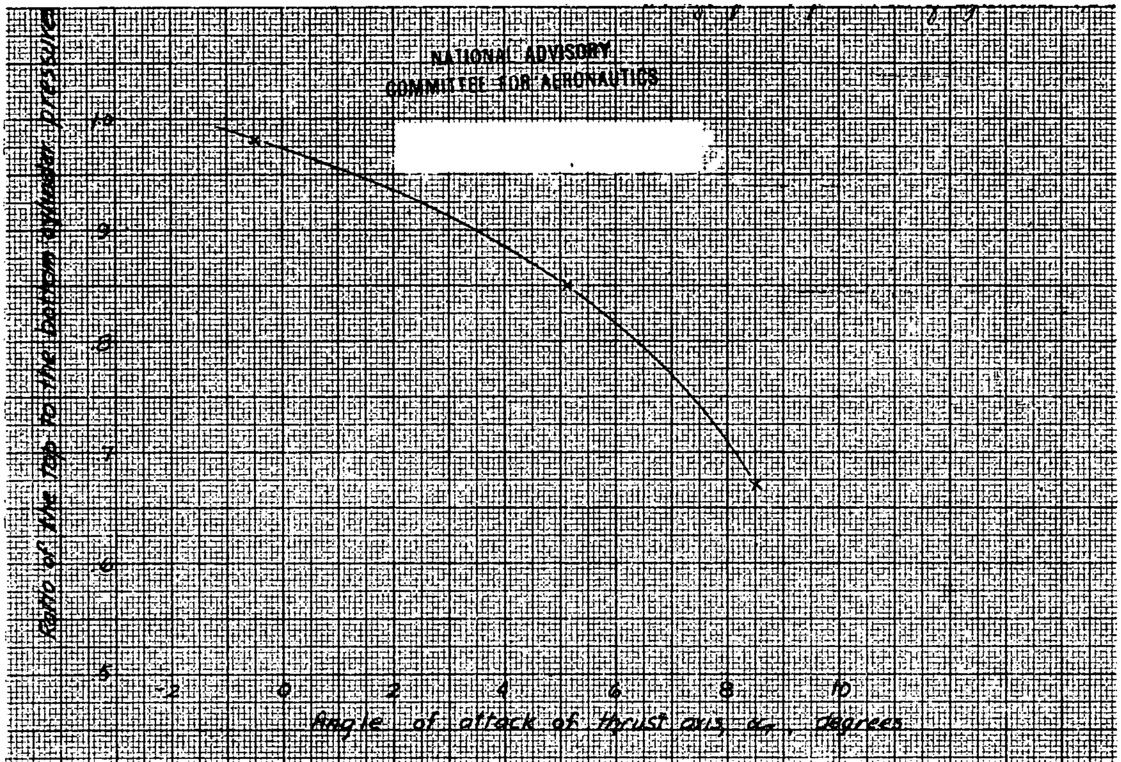

Figure [illegible]. - The effect of angle of attack on the ratio of the top to the bottom cylinder pressures; original condition, flaps open. Points show the ratio of the front pressures on cylinder 1 to the average front pressures of cylinders 7, 8, and 9.

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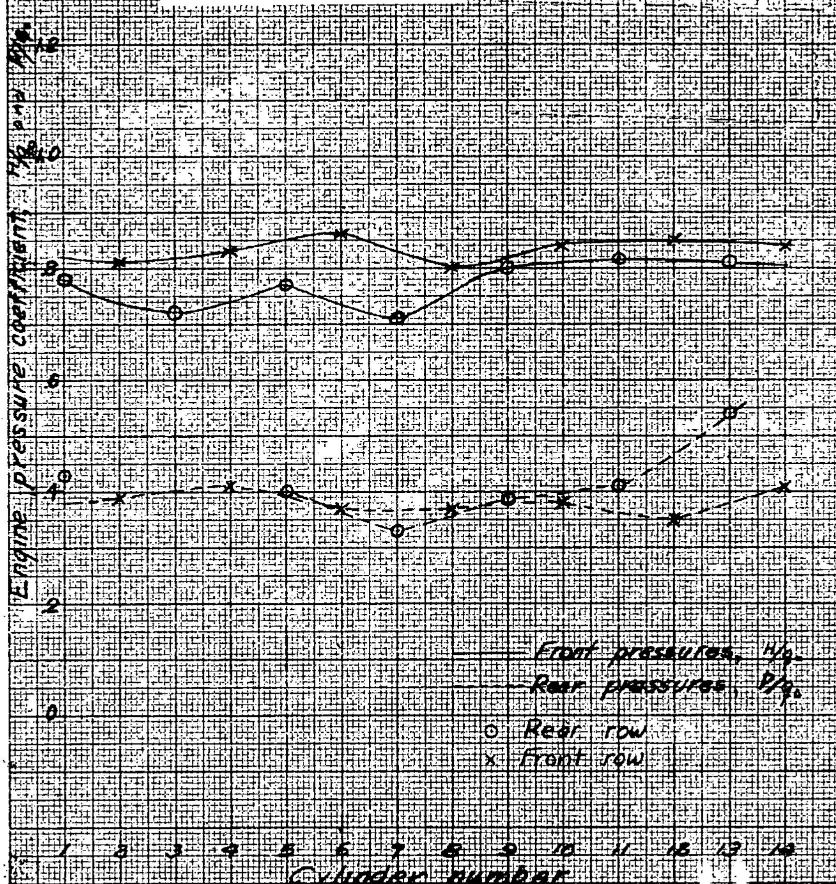


Figure 19. - Variation in the front total and rear static pressures for the original condition, showing difference between the front row and the rear row of cylinders, high-speed attitude.

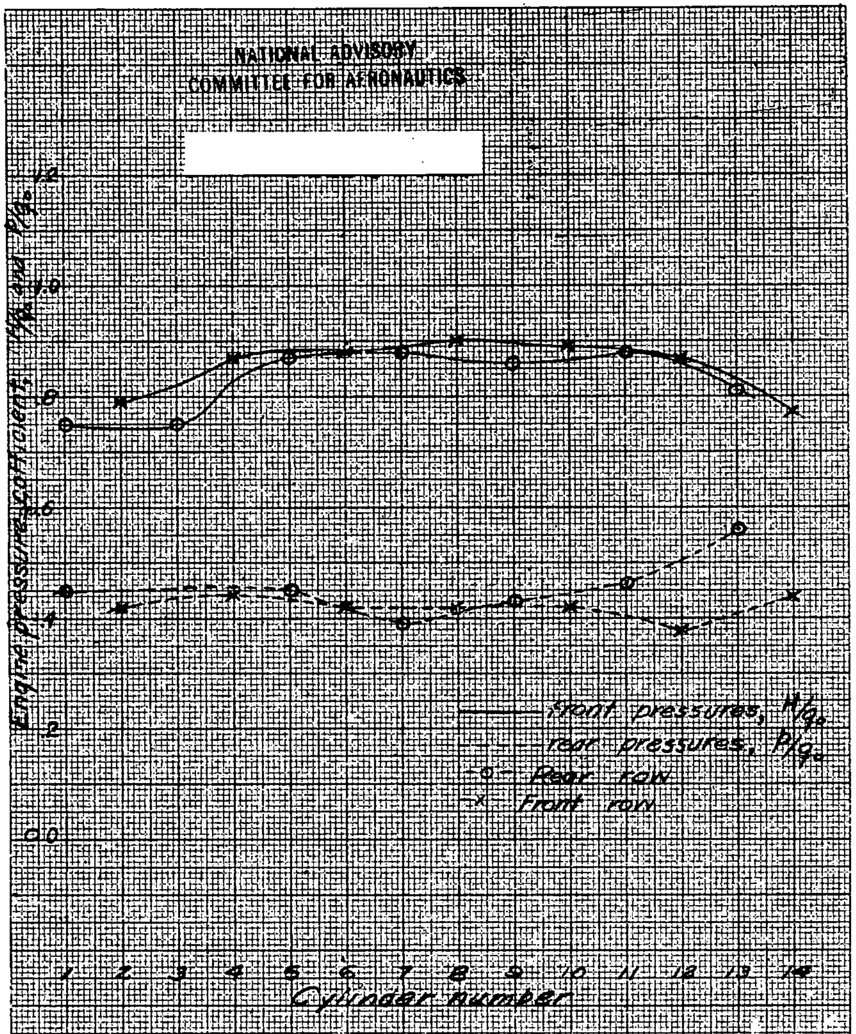


Figure 20. - Variation in front total pressure and rear static pressure for the original condition showing differences between front row and rear row of cylinders; cruising attitude with flaps closed.

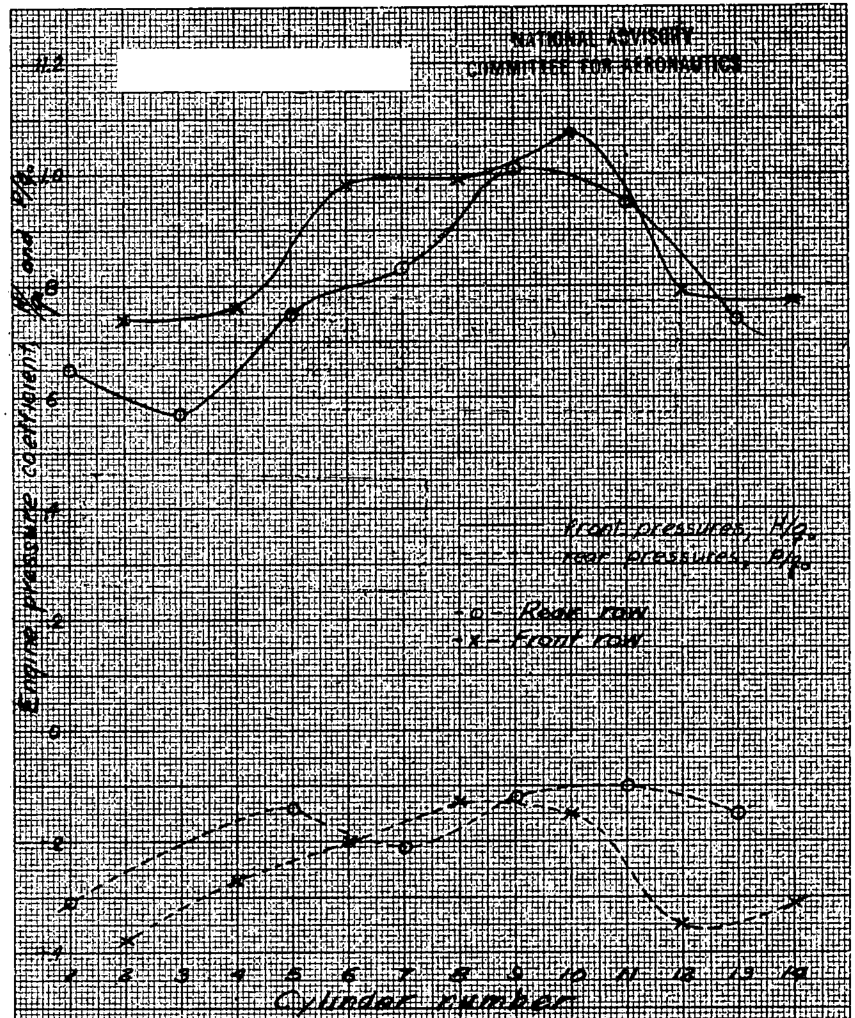
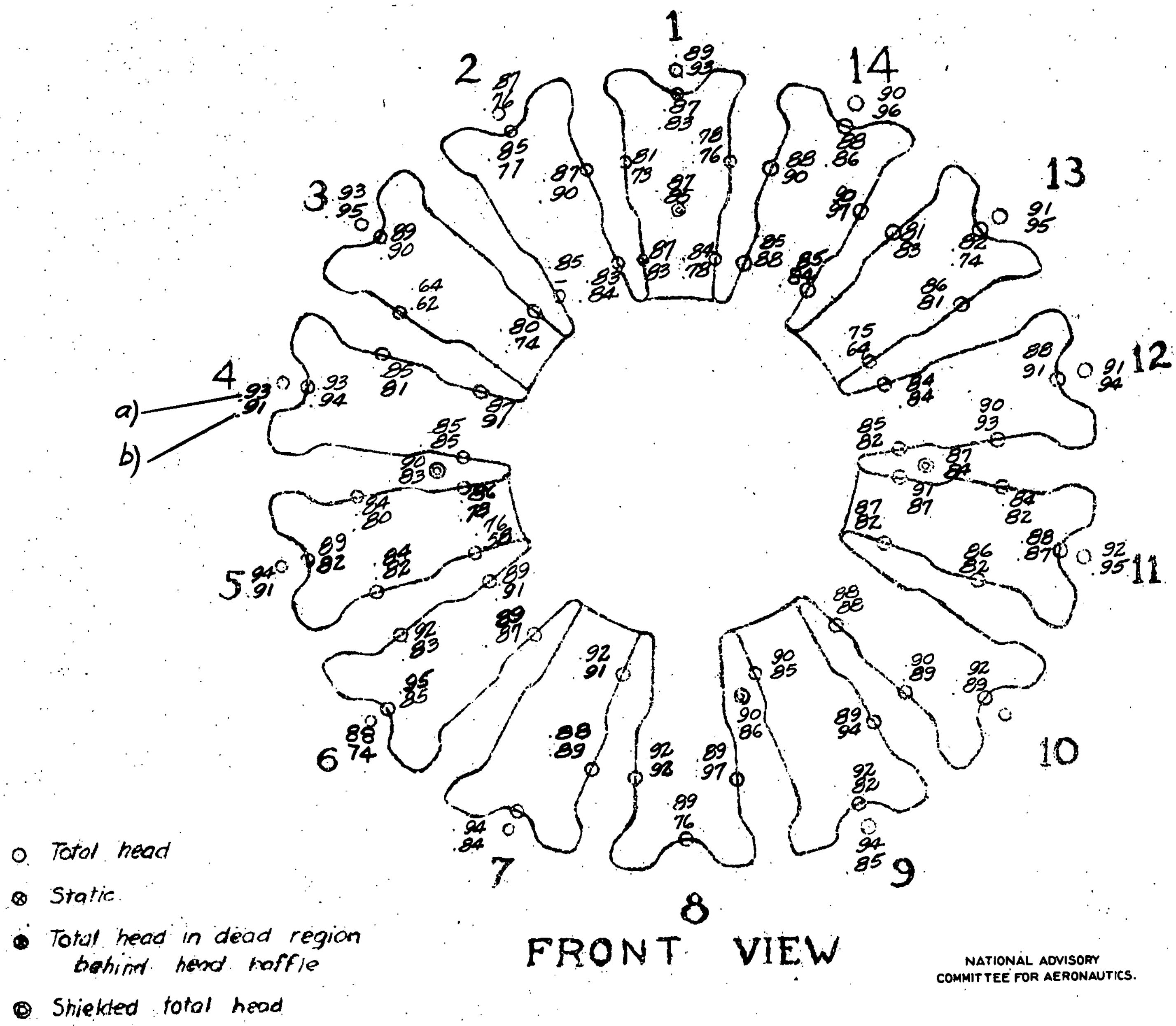


Figure 21. - Variation in the front total and rear static pressures for the original condition, showing the difference between the front row and rear row of cylinders, climb attitude with flaps open.



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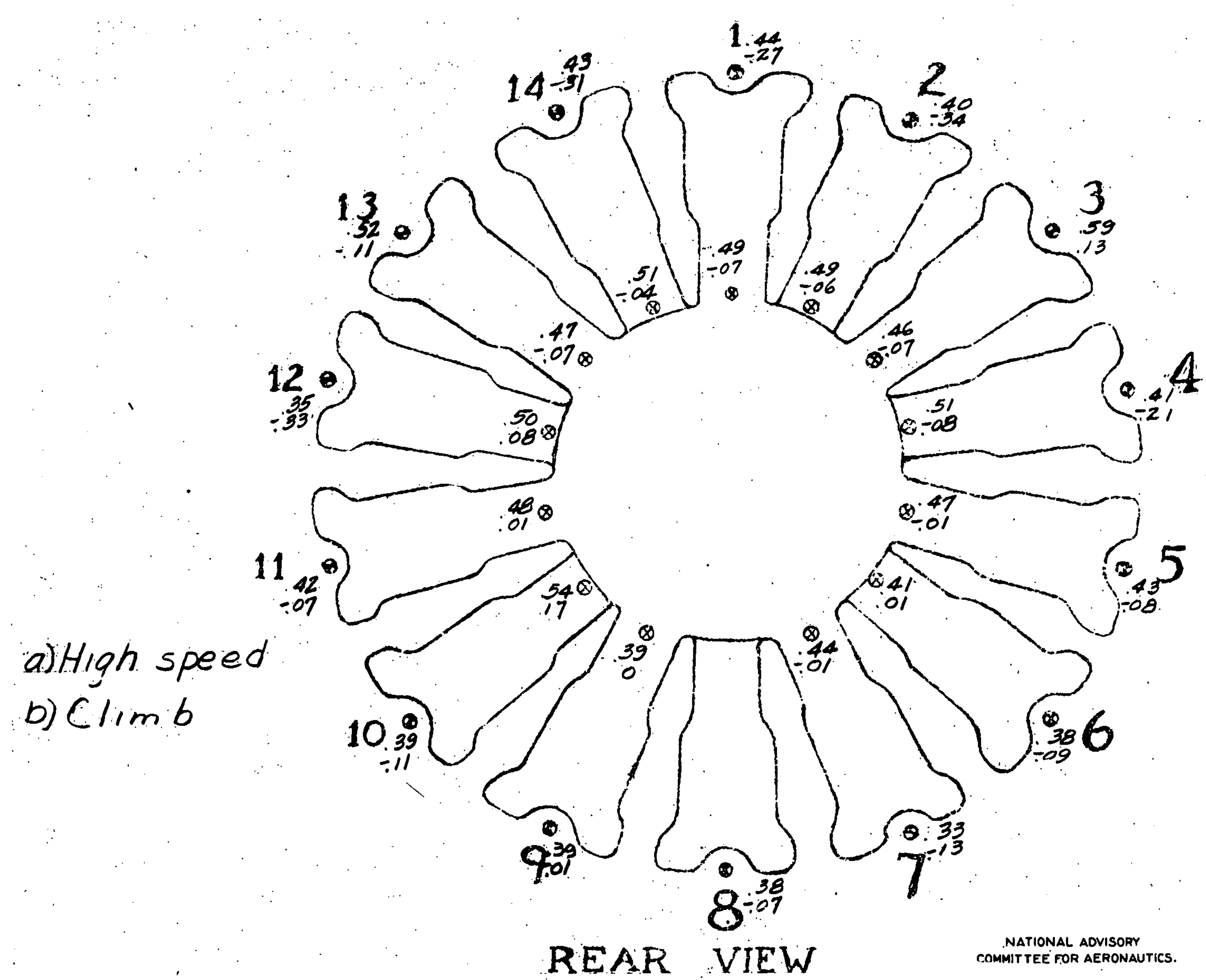

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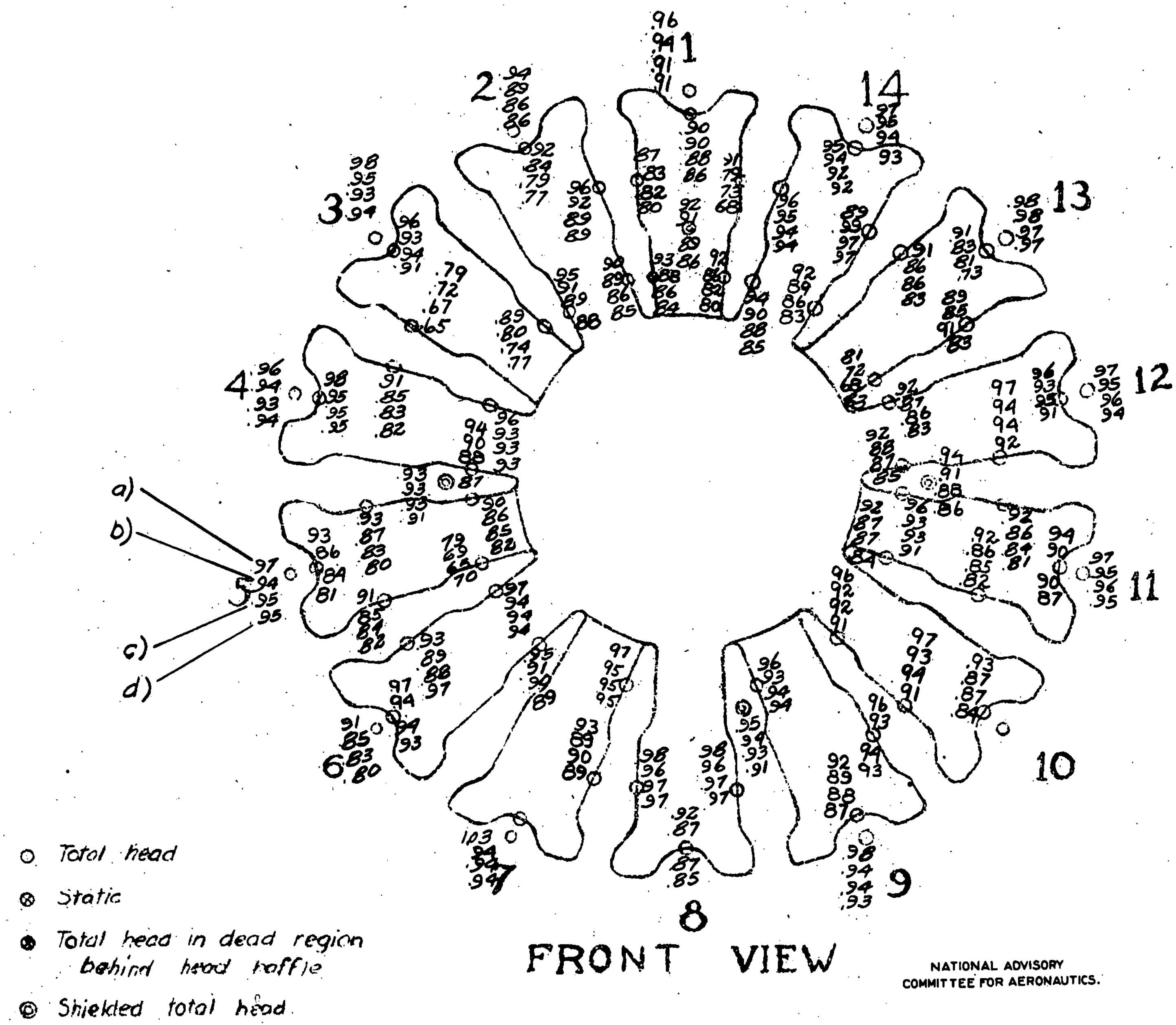
FIGURE 22. - ENGINE PRESSURE DISTRIBUTION FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION IN HIGH SPEED AND CLIMB ATTITUDE; POWER OFF.



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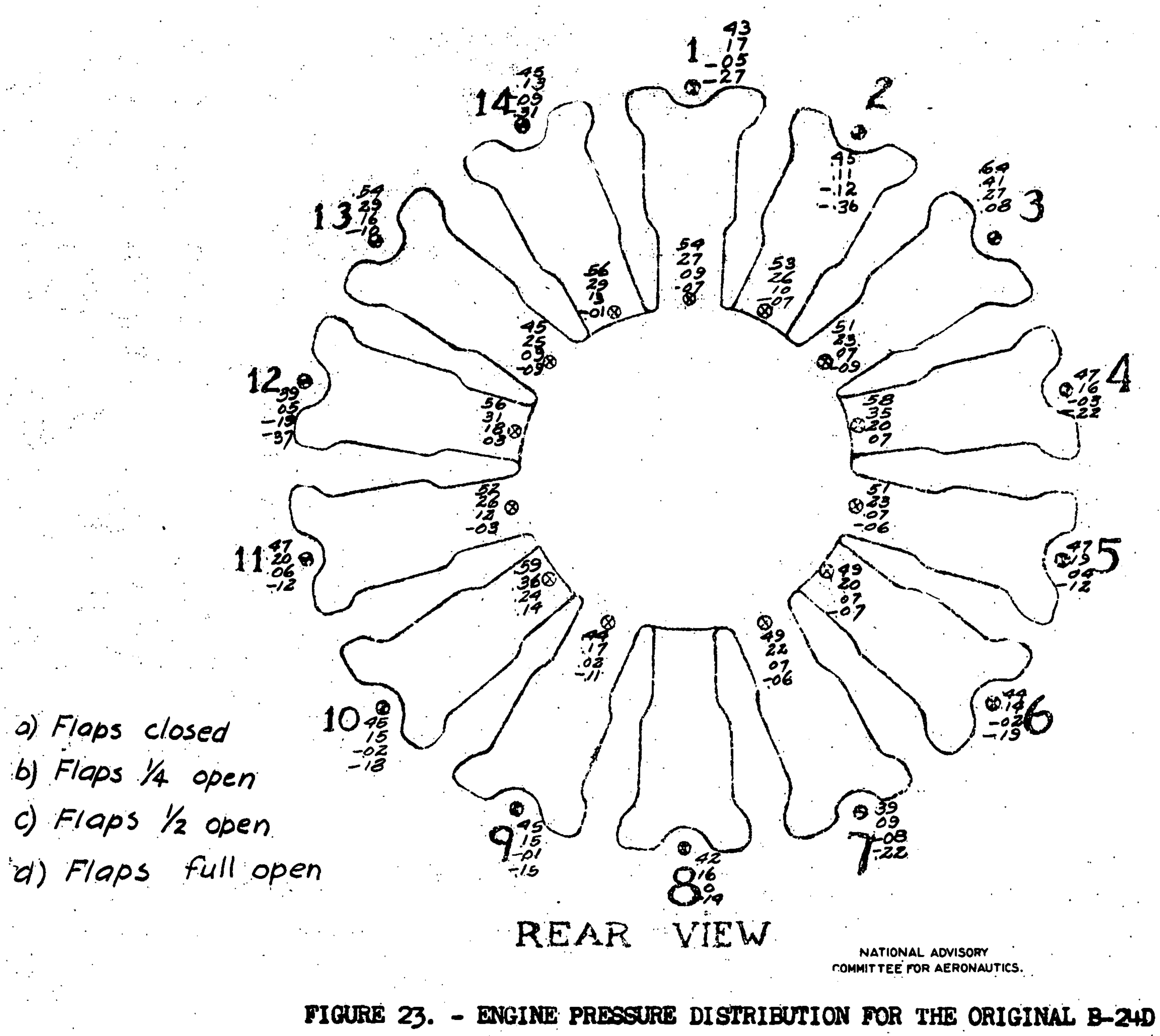

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FIGURE 23. - ENGINE PRESSURE DISTRIBUTION FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION IN CRUISING ATTITUDE; POWER OFF.

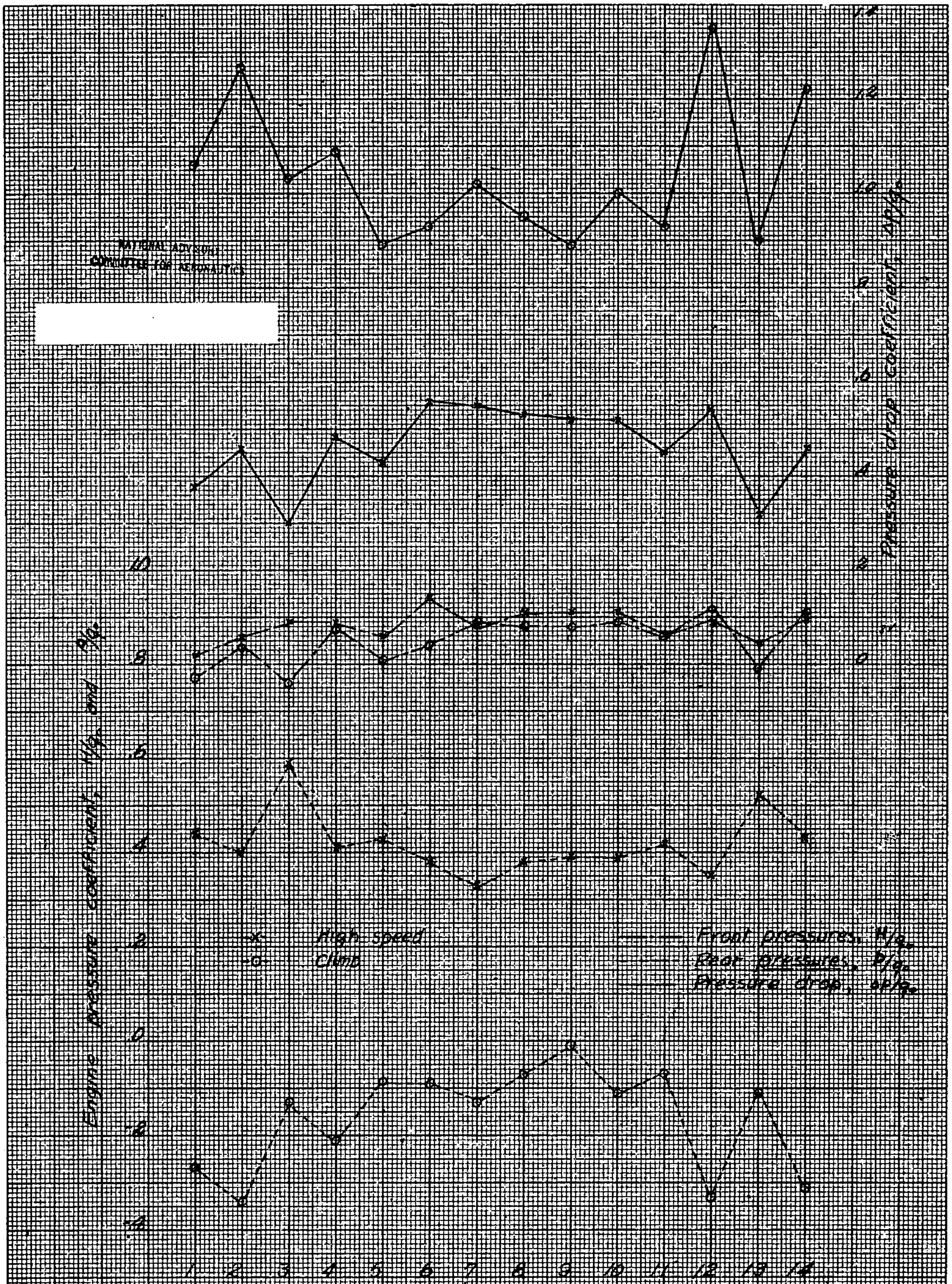


Figure 24. - Variation of the front and rear head pressures and the pressure drop for high speed and climb; power off, original condition.

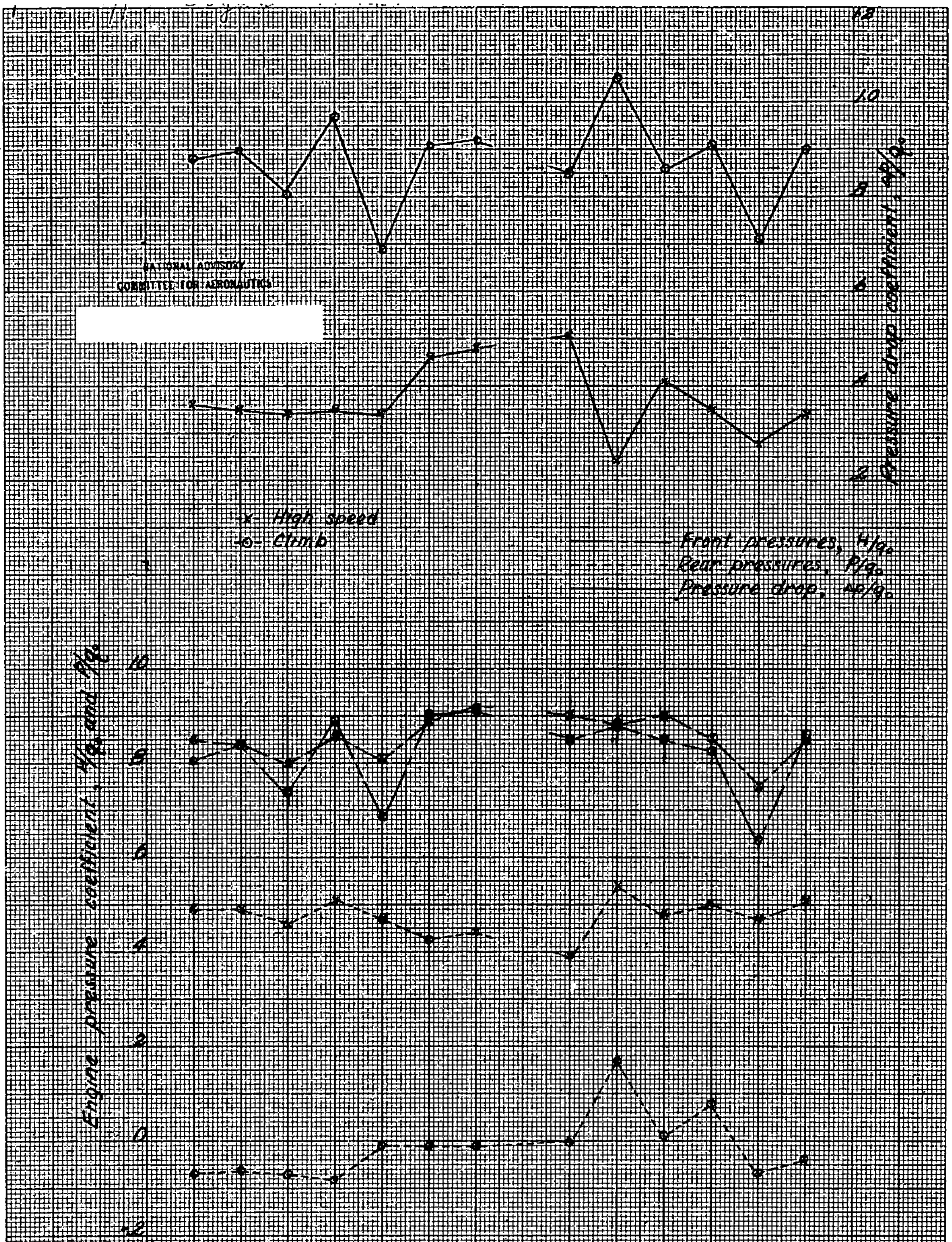


Figure 25. - Variation of the front and rear barrel pressures and the pressure drop for high speed and climb; power off; original condition.

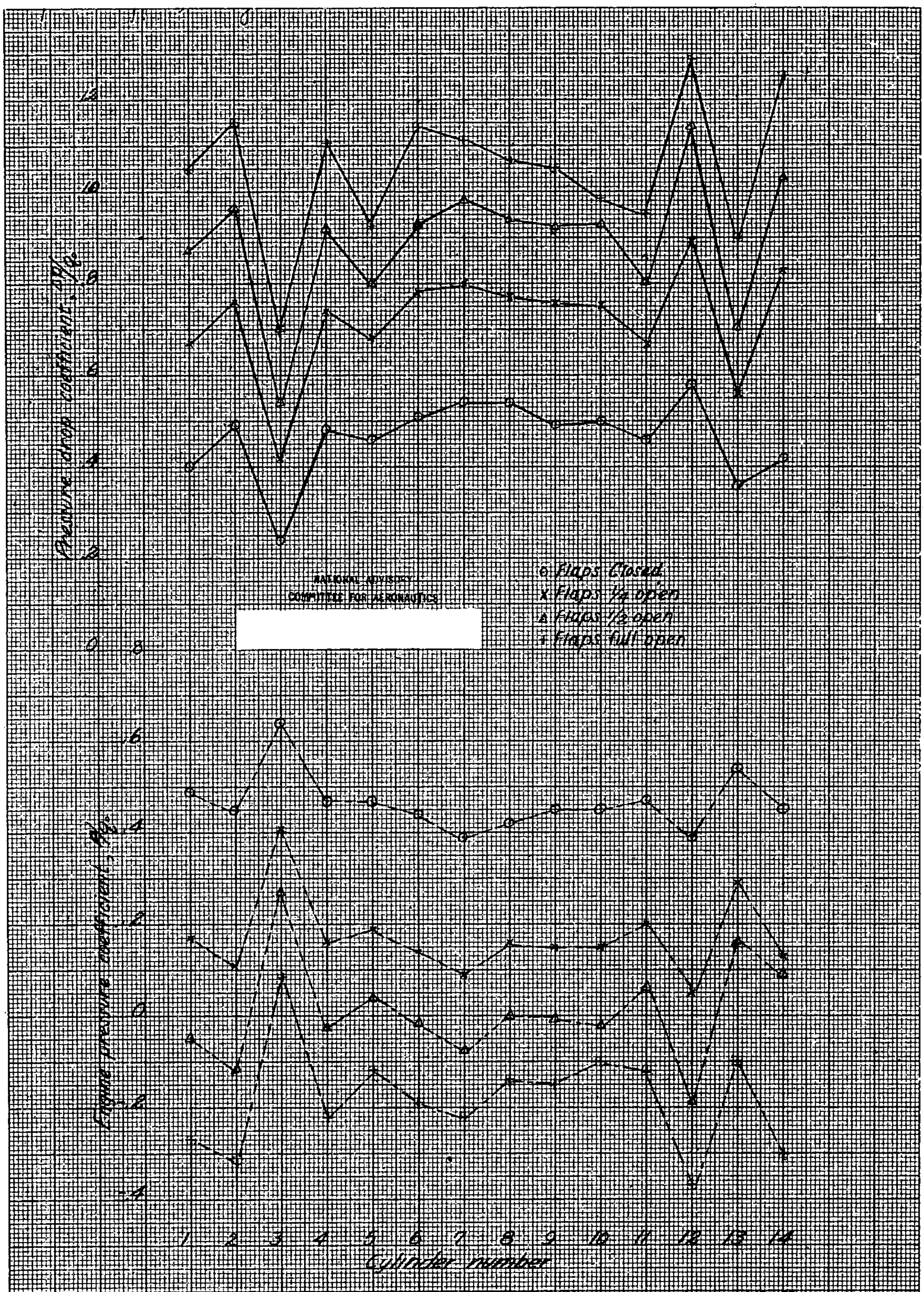


Figure 26. - Variation of the rear head pressures and the pressure drops with flap angles in cruising; power off; original condition.

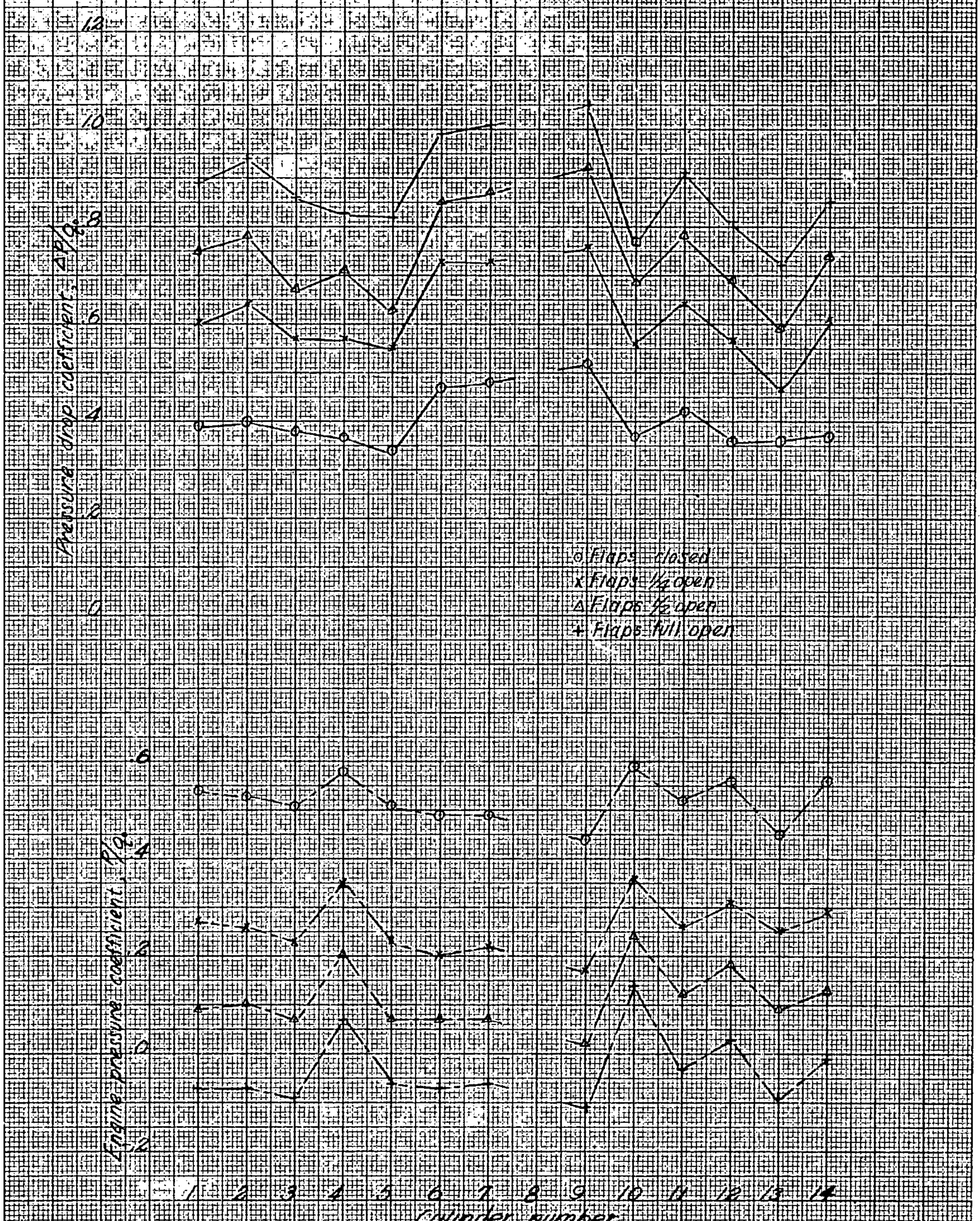


Figure 27. - Variation of the rear barrel pressures and the pressure drop with flap angles for cruising, power off; original condition.

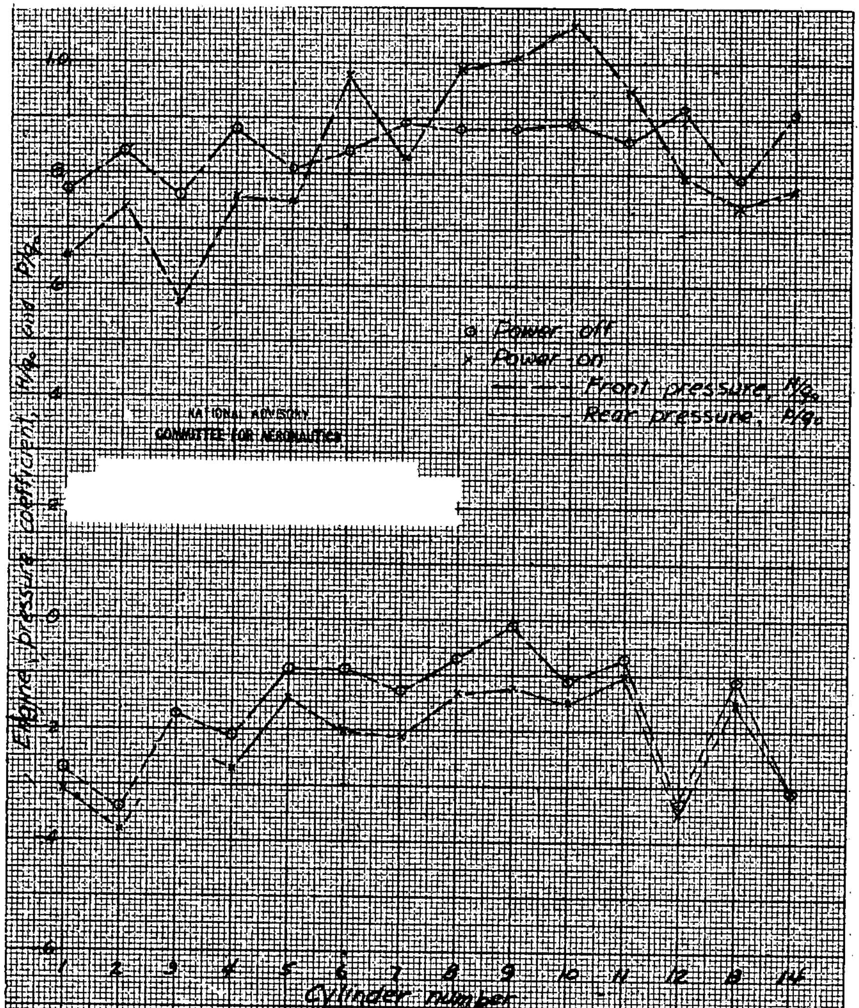


Figure 28. - Comparison of power-on and power-off pressure distribution on the heads for the original condition in climb.

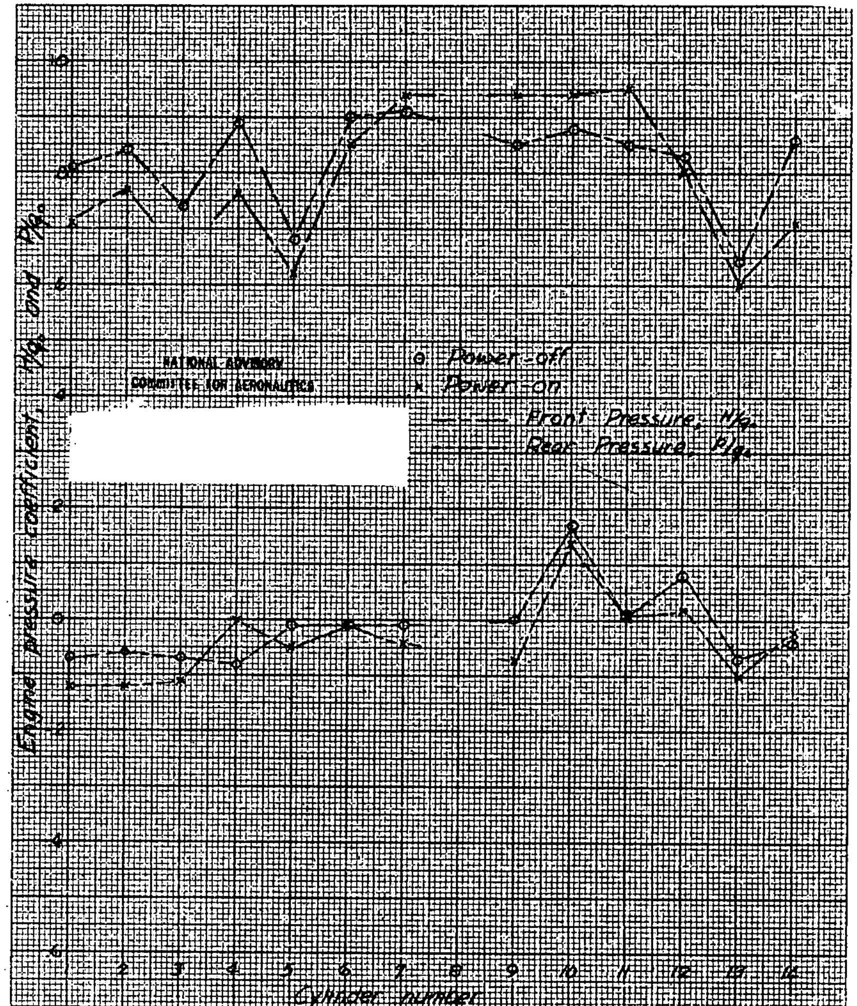
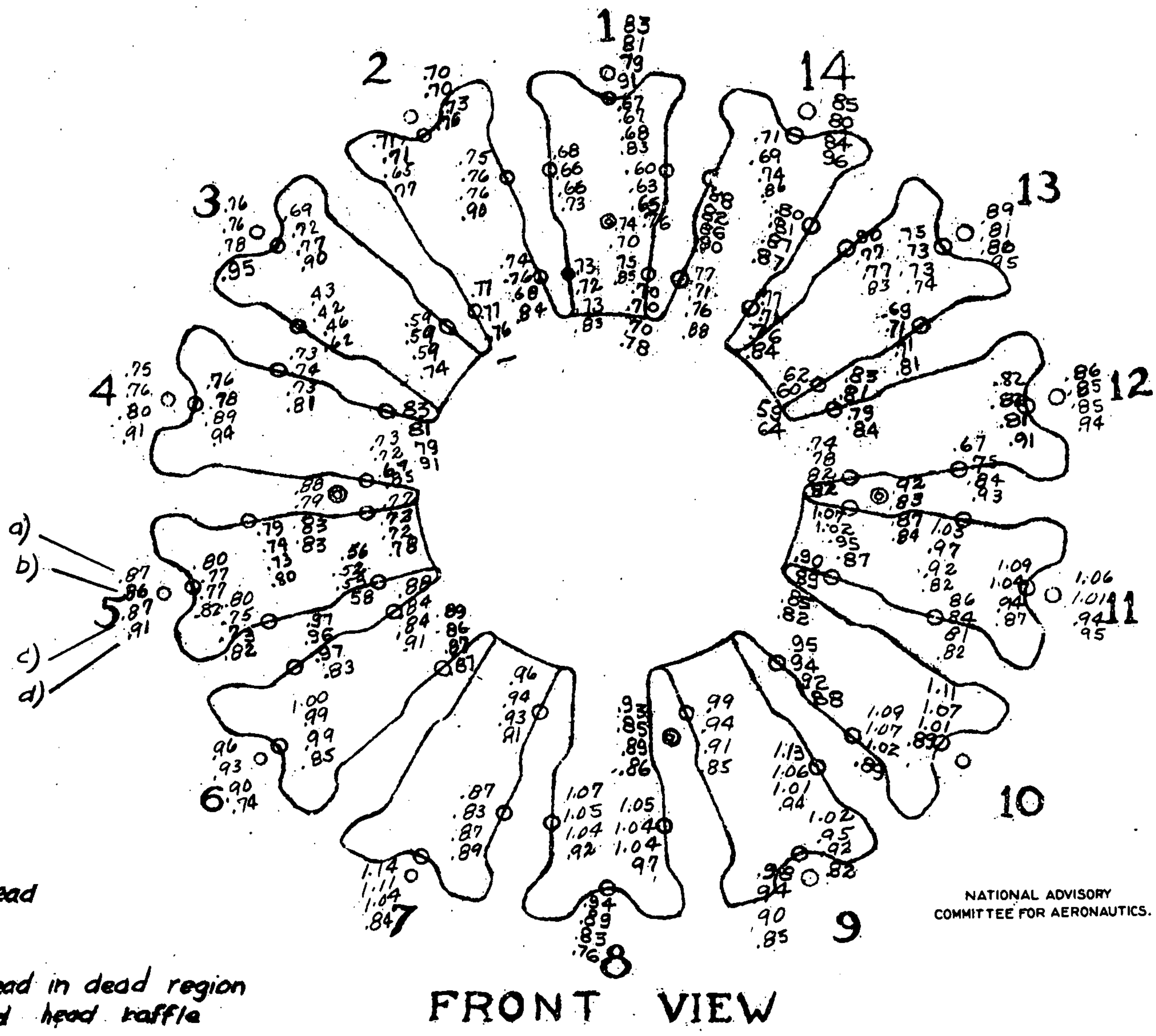


Figure 29. - Comparison of power-off and power-on pressure distribution on the barrels for the original condition in climb.

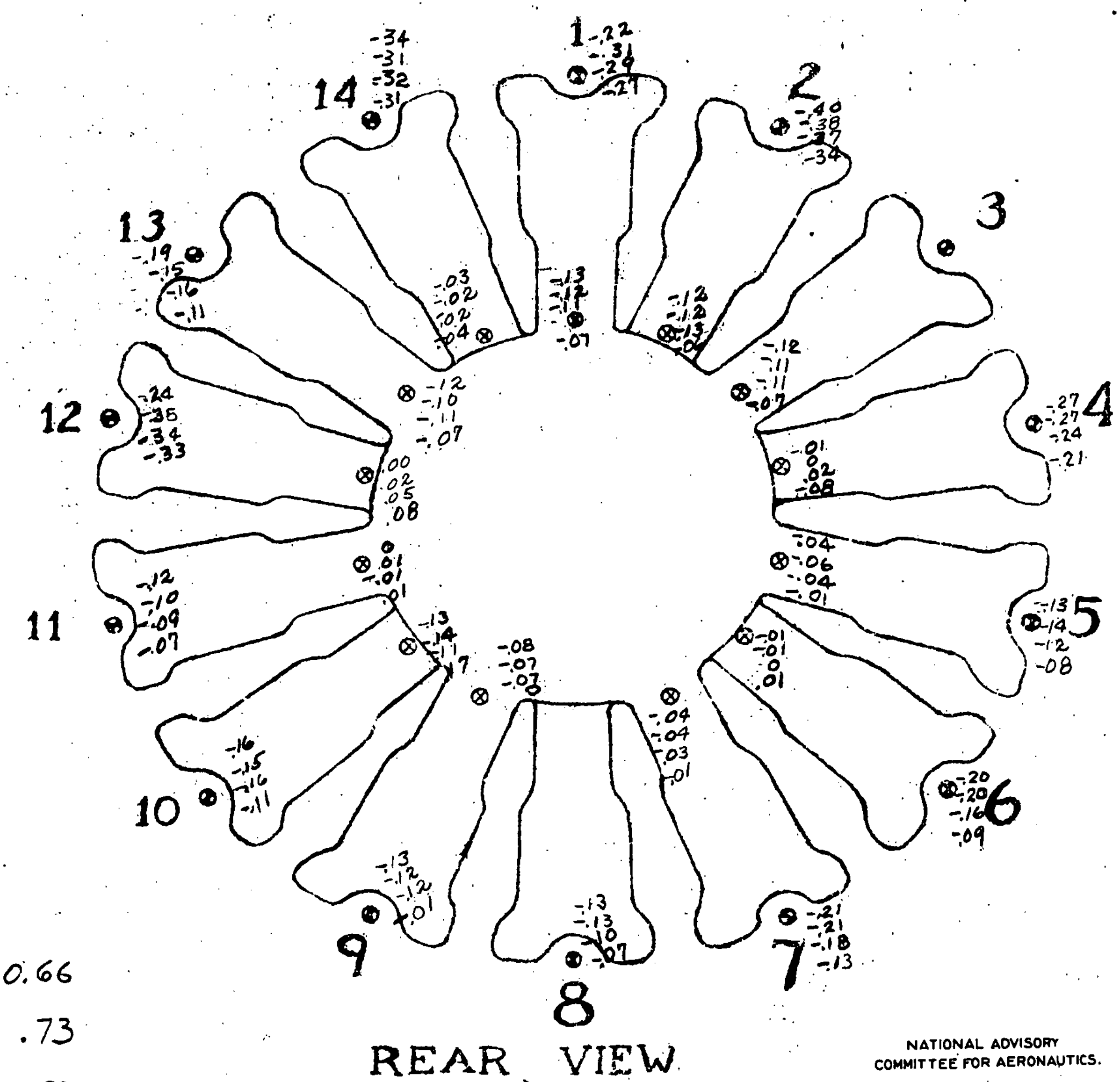


○ Total head

⊗ Static

● Total head in dead region behind head baffle

⊛ Shielded total head



a) $V/nD = 0.66$

b) $V/nD = .73$

c) $V/nD = .83$

d) Power off

FIGURE 30. - VARIATION IN ENGINE PRESSURE DISTRIBUTION WITH PROPELLER THRUST FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION; CLIMB ATTITUDE.

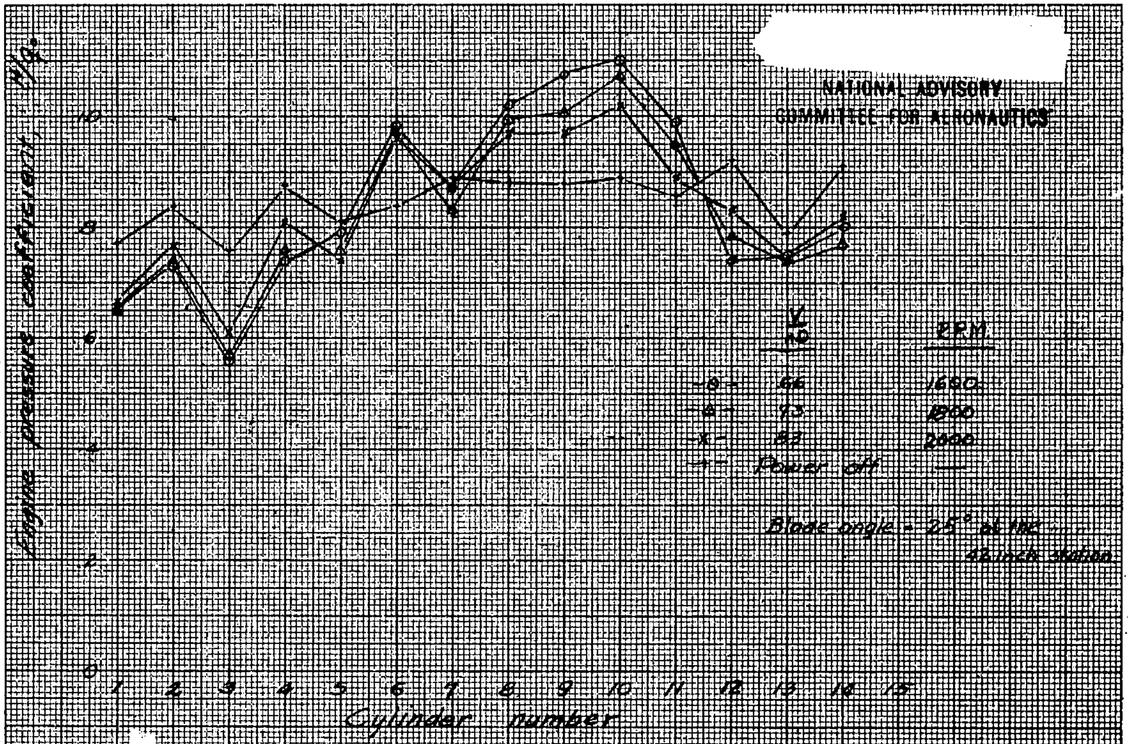
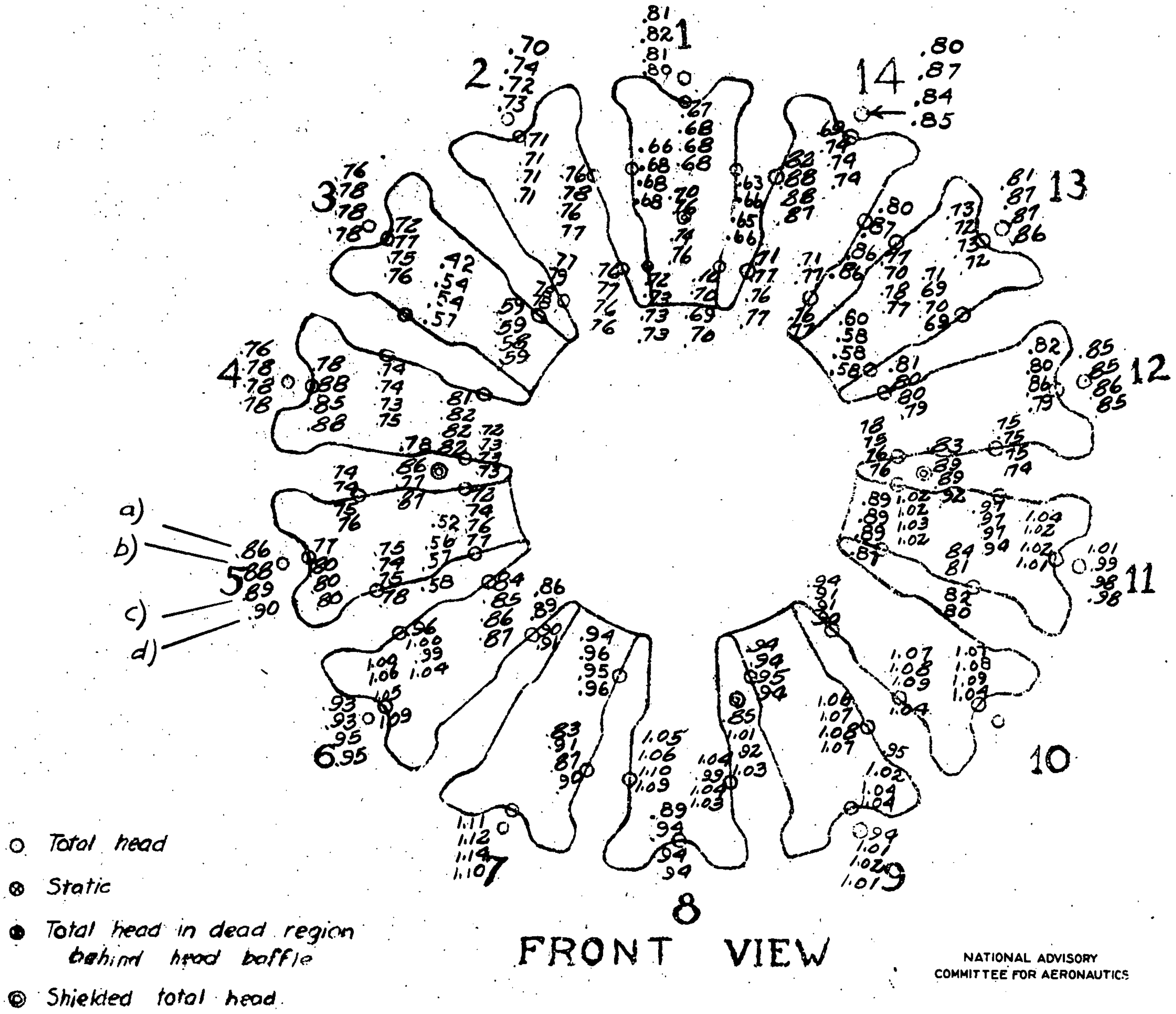


Figure 31. - Variation of the front head pressures with V/nD; climb attitude.



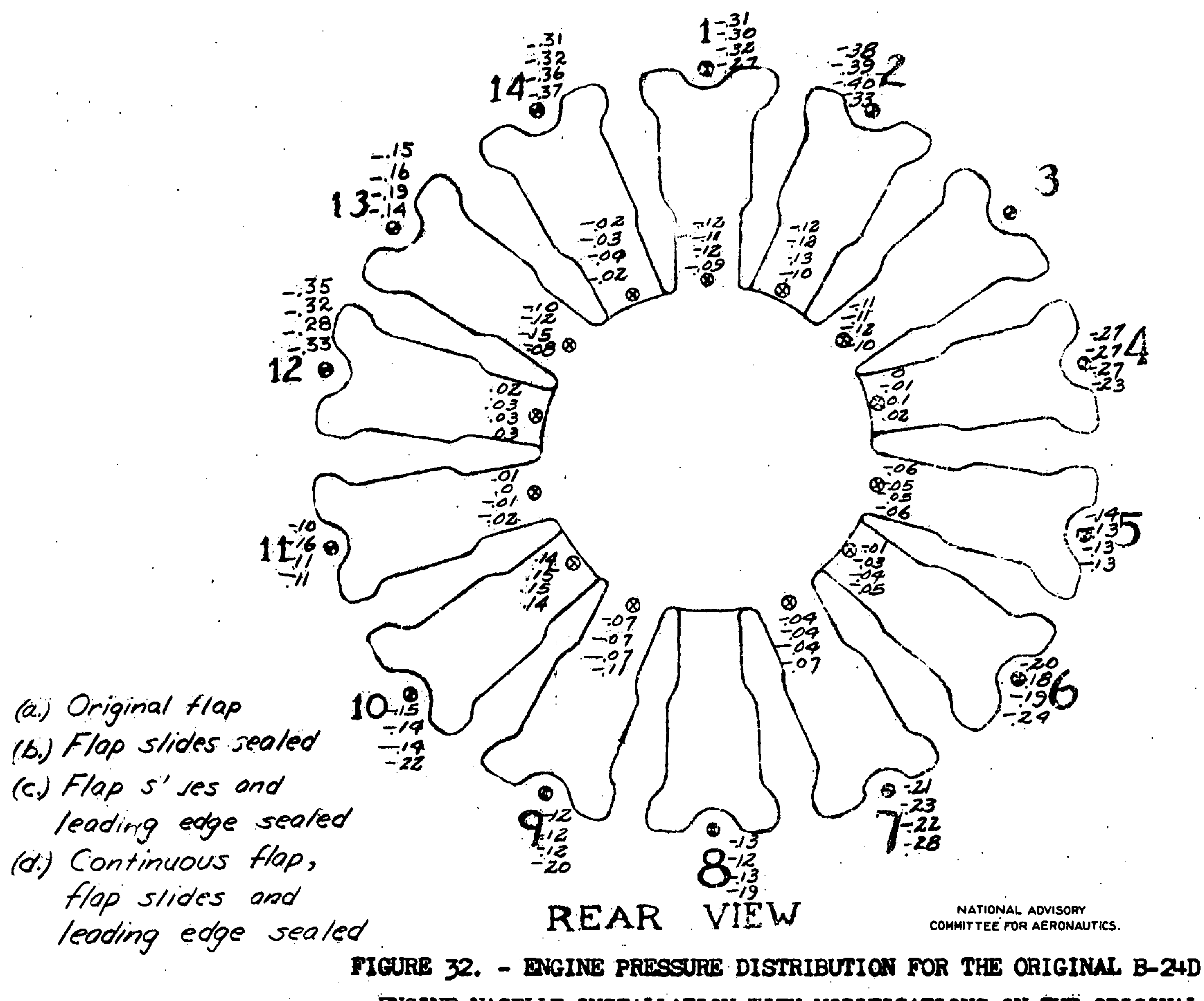
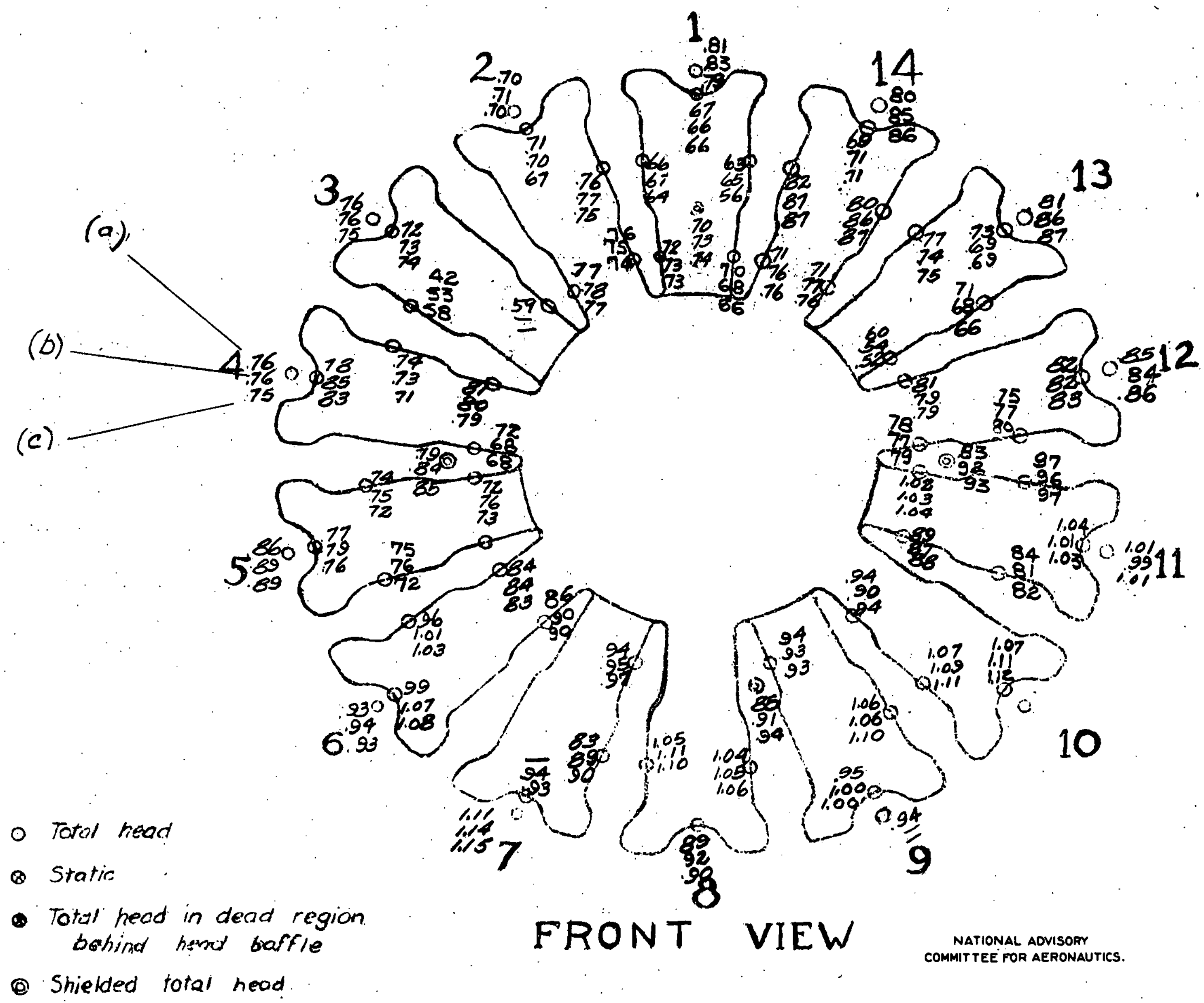


FIGURE 32. - ENGINE PRESSURE DISTRIBUTION FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION WITH MODIFICATIONS ON THE ORIGINAL COWL FLAPS; CLIMB



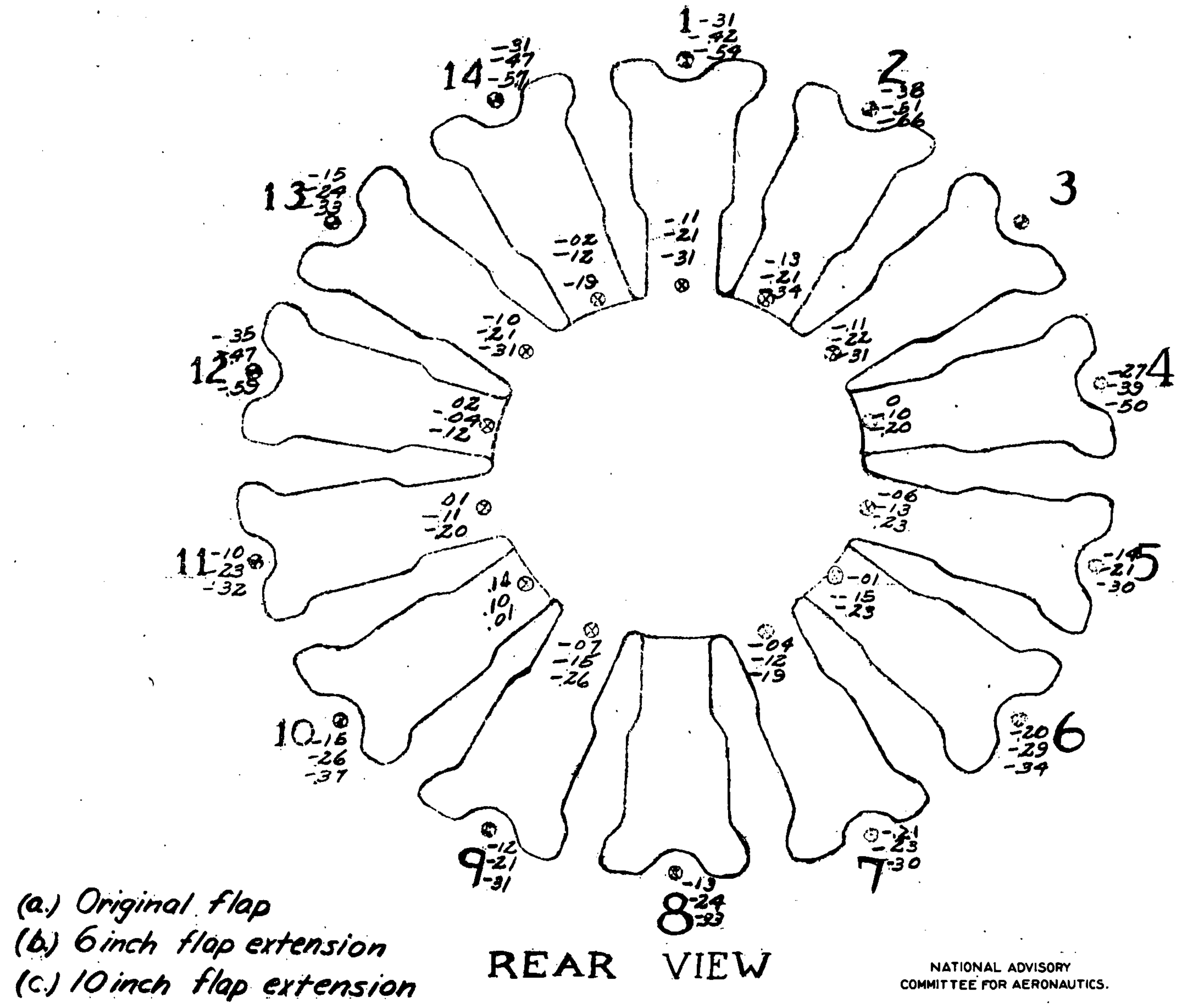


FIGURE 33. - ENGINE PRESSURE DISTRIBUTION FOR THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION WITH THE 6-INCH AND THE 10-INCH COWL FLAP EXTENSIONS; CLIMB ATTITUDE.

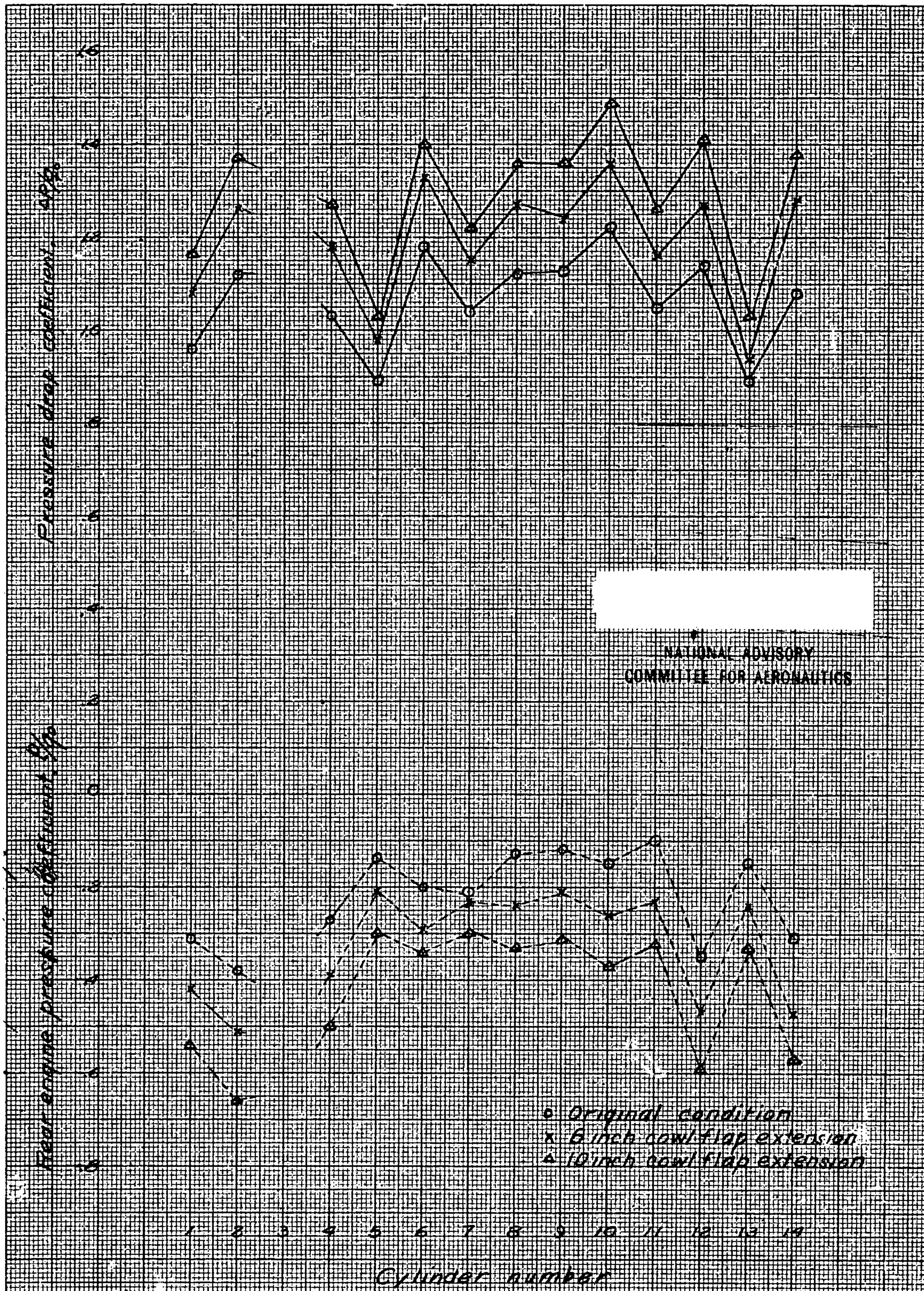


Figure 35. - Variation in the rear engine pressures and the pressure drop across the head for the 6-inch and the 10-inch cowl flap extension on the B-24D engine-nacelle installation.

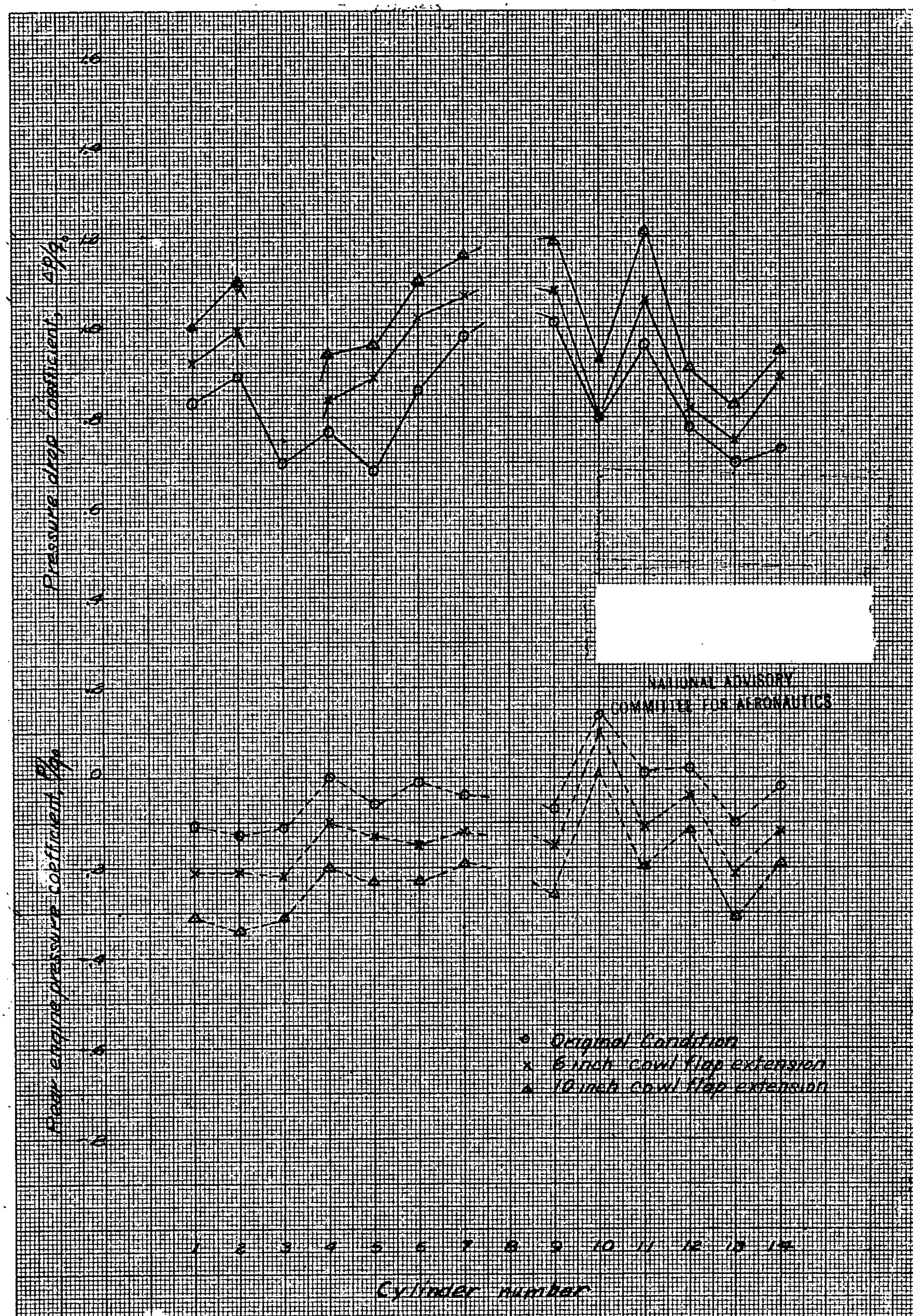


Figure 35. - Variation in rear engine pressures and the pressure drops across the barrels for the 6-inch and the 10-inch cowl flap extensions on the B-240 engine-nacelle installation.

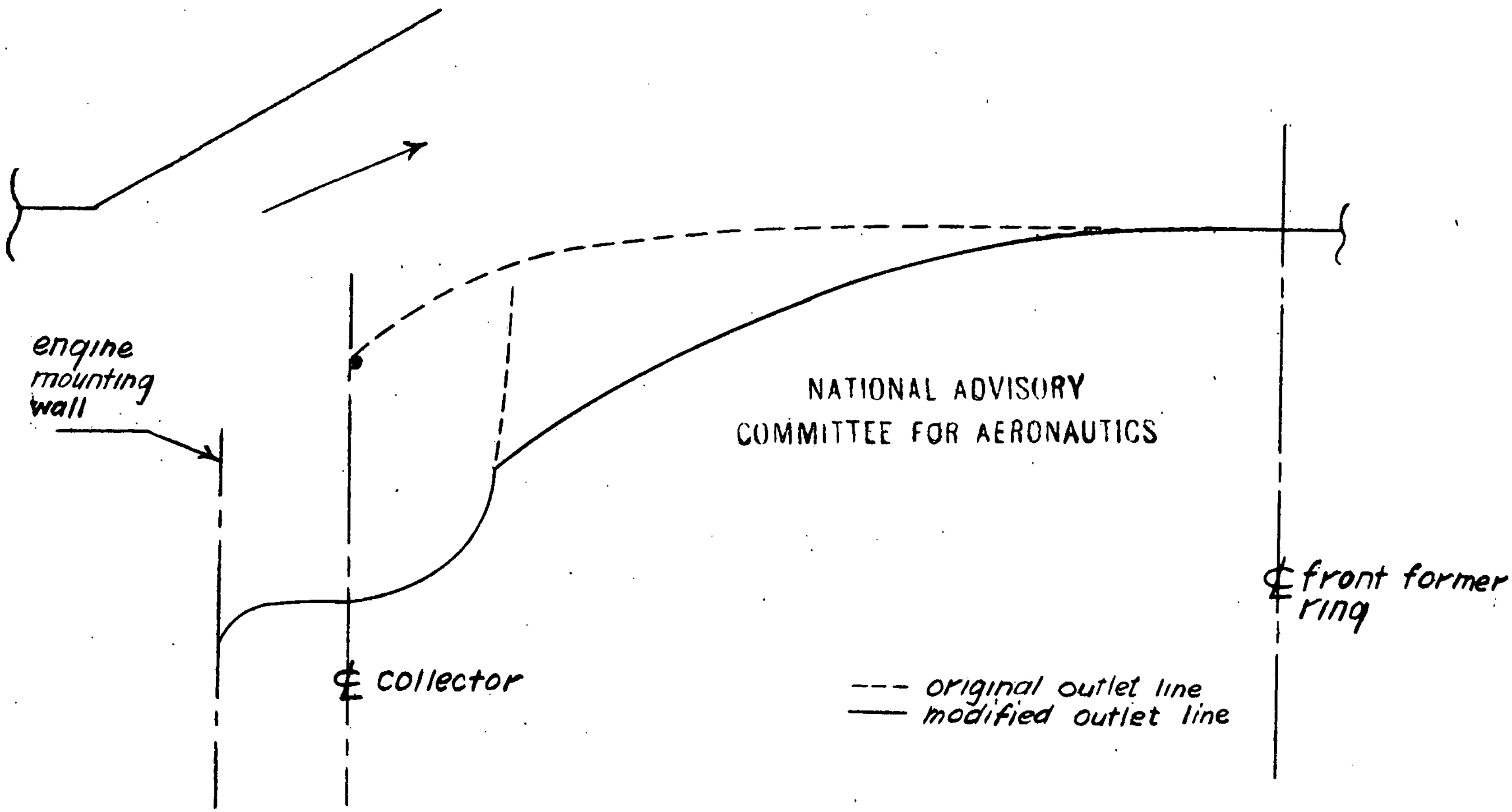


Figure 36.- Original and modified cowl outlet on the B-24D nacelle installation.

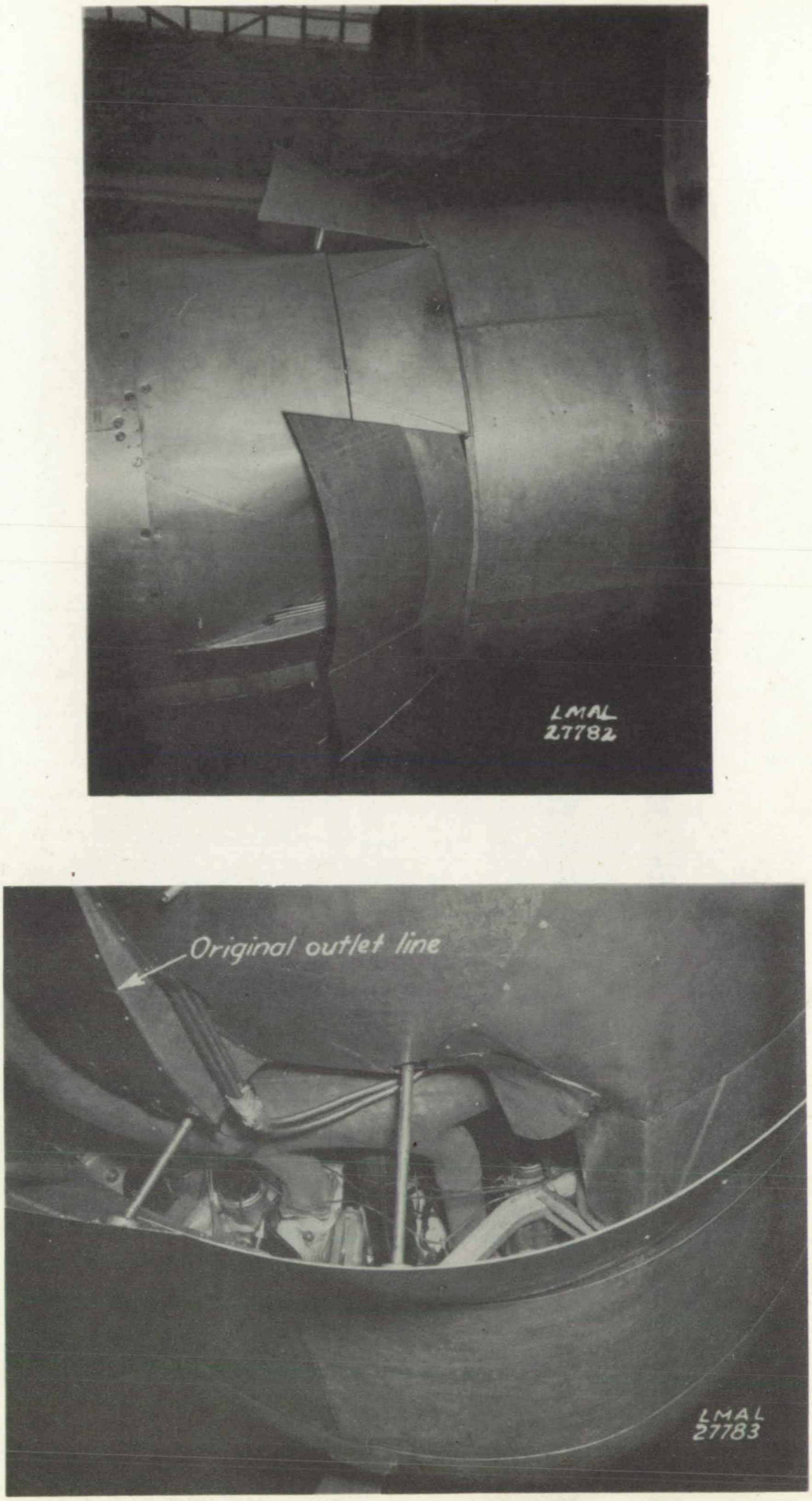


Figure 37.- Modified cowl outlet with 6-inch cowl flap extension.

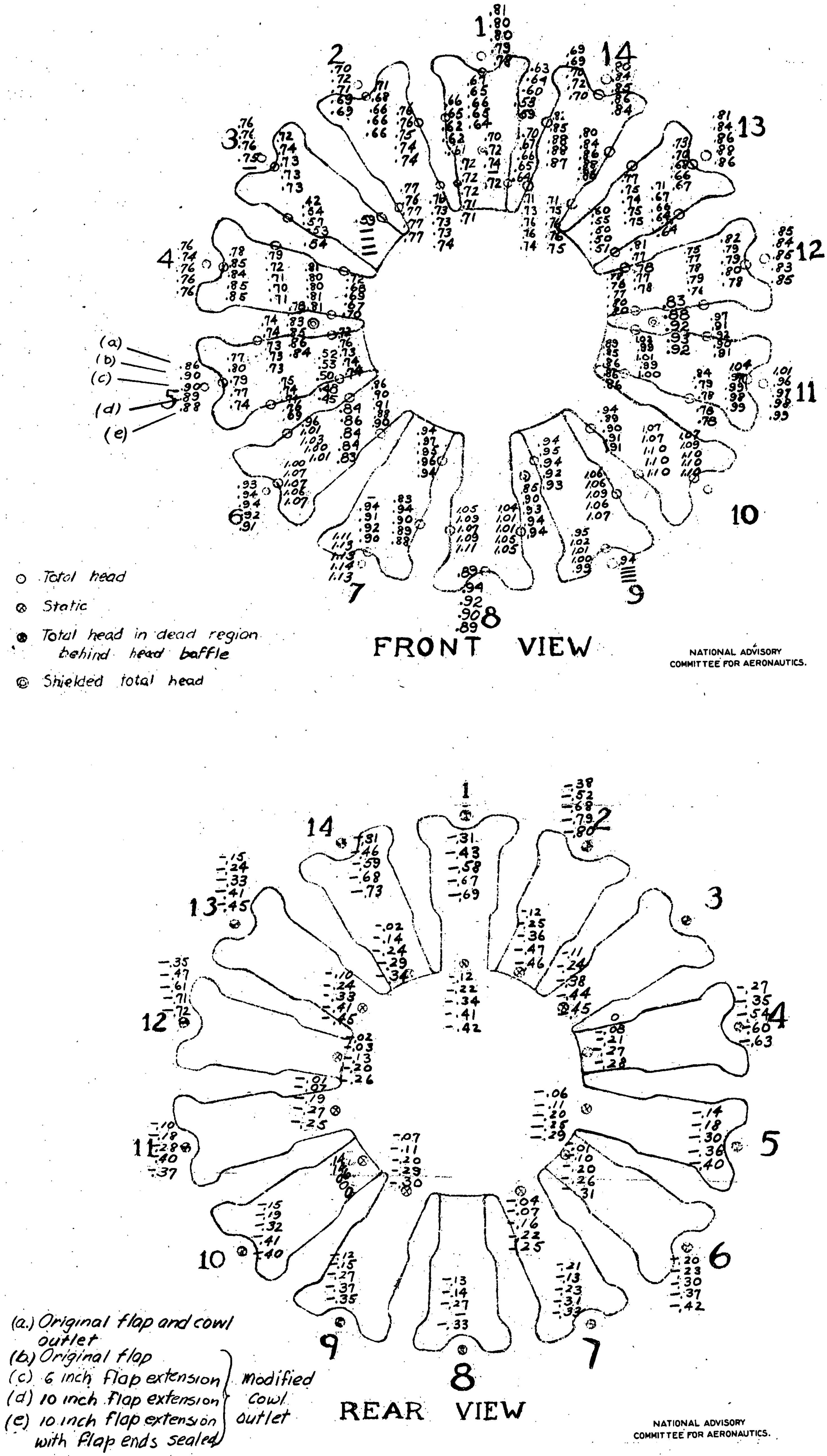


FIGURE 38. - ENGINE PRESSURE DISTRIBUTION ON THE ORIGINAL B-24D ENGINE-NACELLE INSTALLATION WITH THE MODIFIED COWL OUTLET AND THE EXTENDED COWL FLAPS; CLIMB

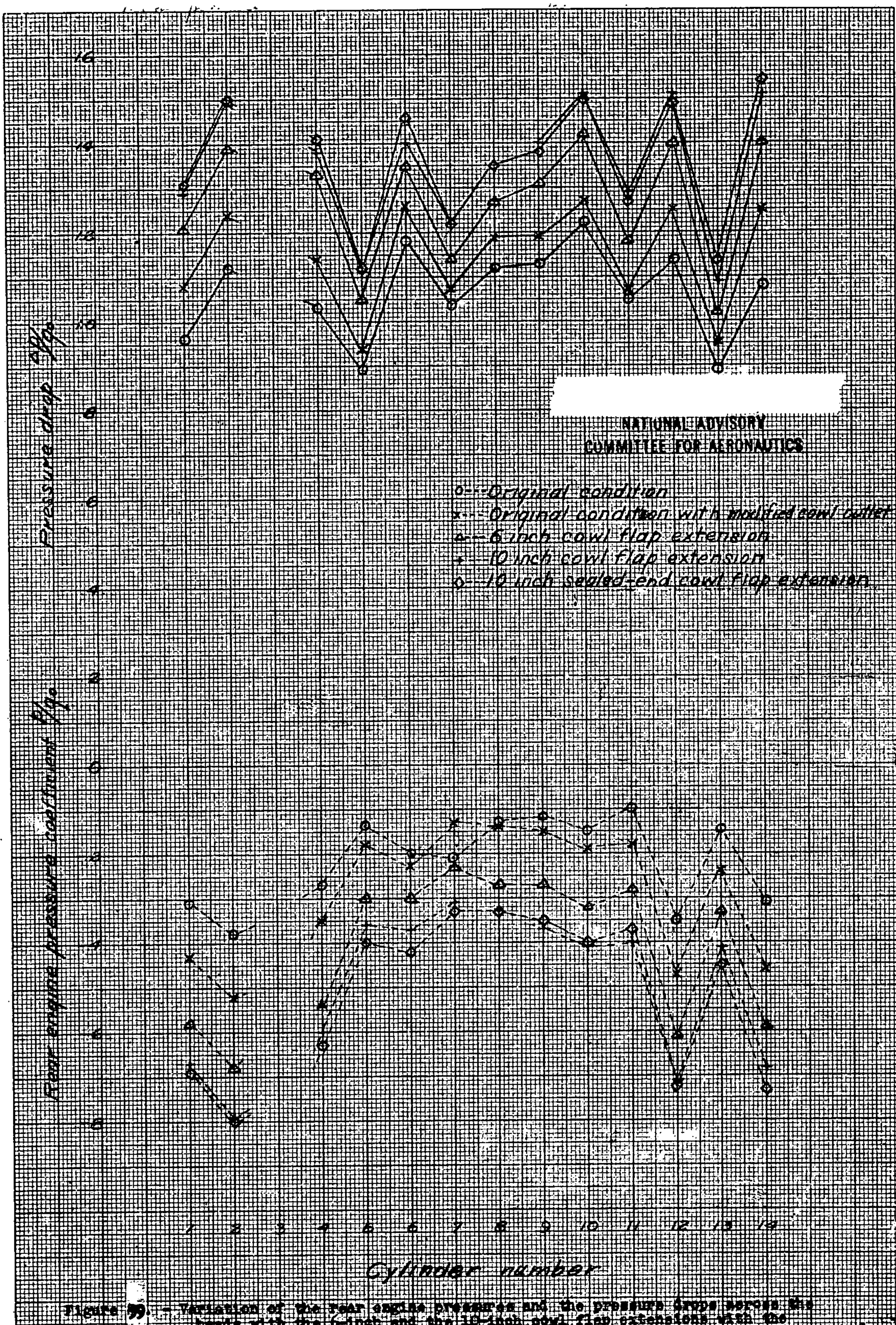


Figure 99. - Variation of the rear engine pressures and the pressure drops across the heads with the 6-inch and the 10-inch cowl flap extensions with the modified cowl outlet, on the B-24D engine-nacelle installation. Climb attitude.

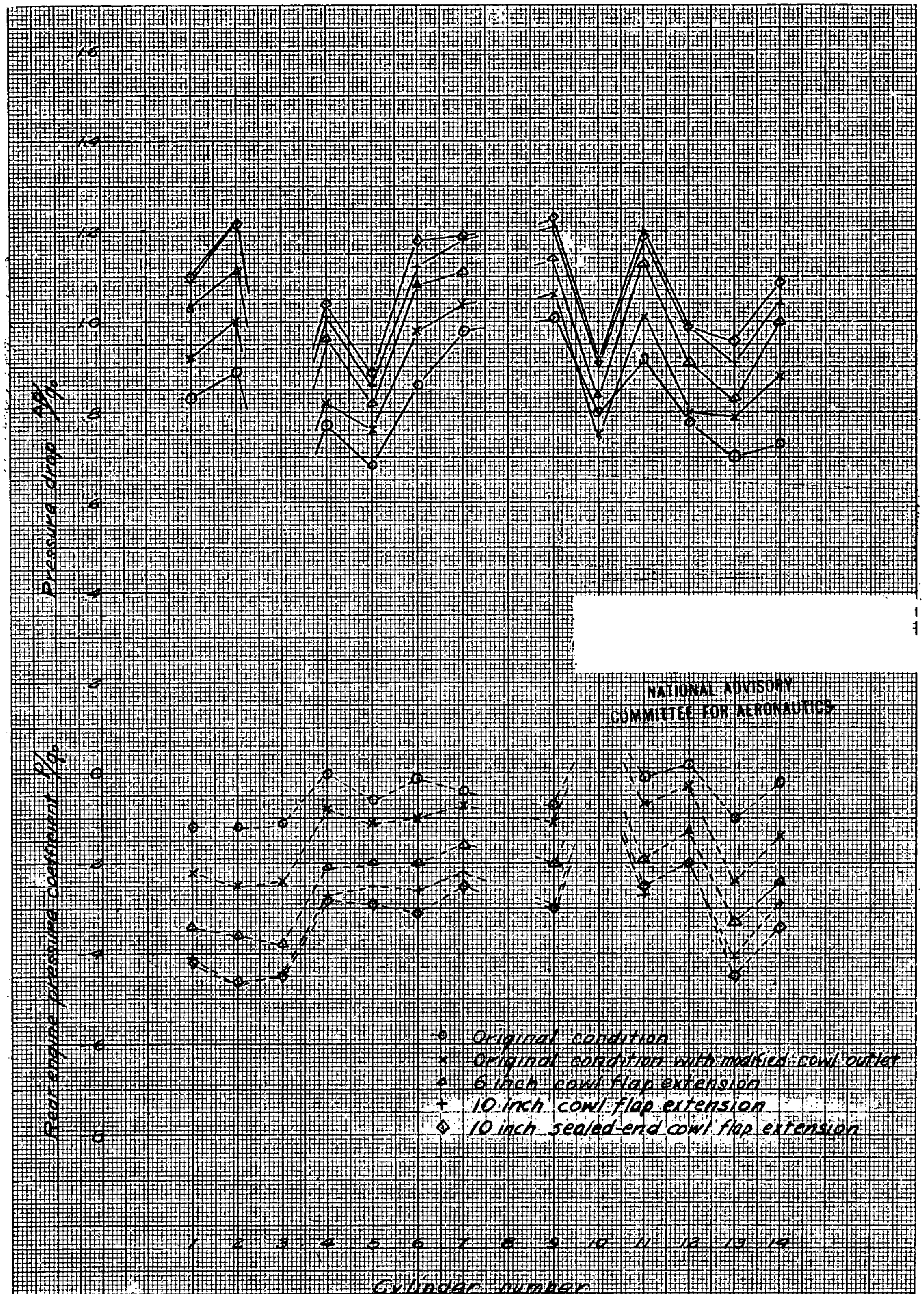


Figure 49. - Variation in the rear engine pressures and the pressure drops for barrels with the 6-inch and the 10-inch cowl flap extensions and the modified cowl outlet on the B-24D engine-nacelle installation. Climb attitude

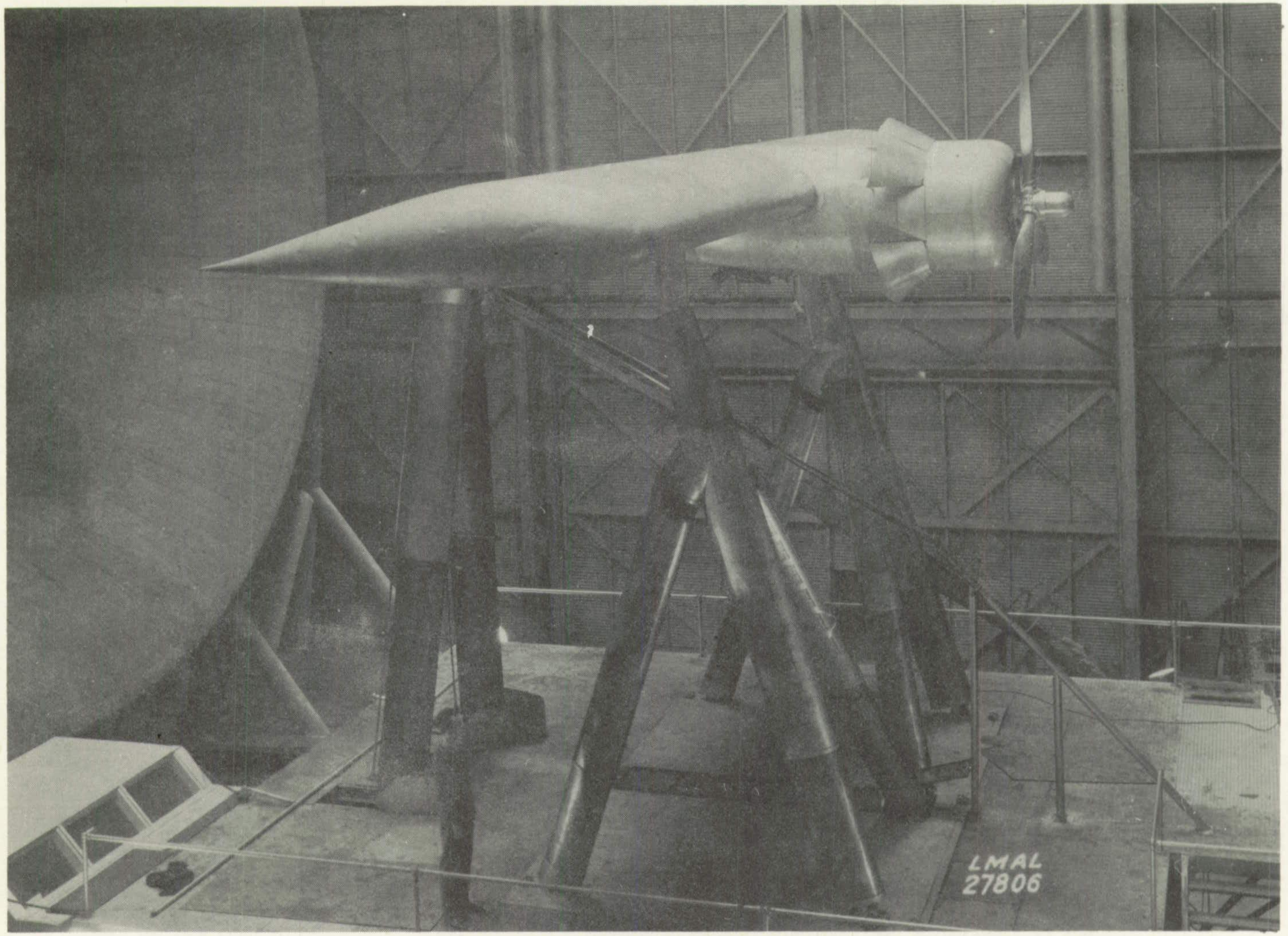


Figure 41.- The 10-inch extended cowl flap with the modified cowl outlet on the B-24D engine-nacelle installation.

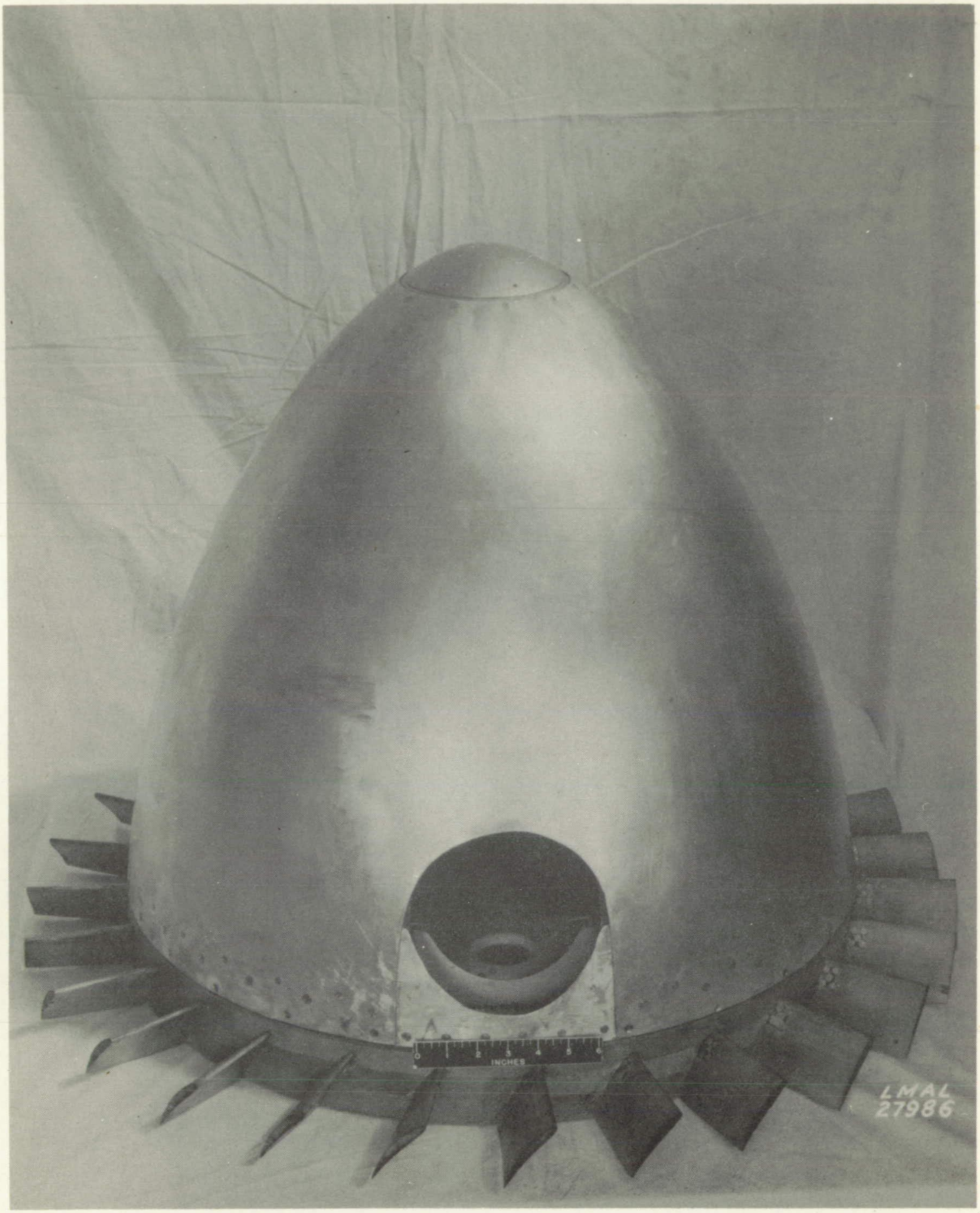


Figure 42.- Spinner blower.

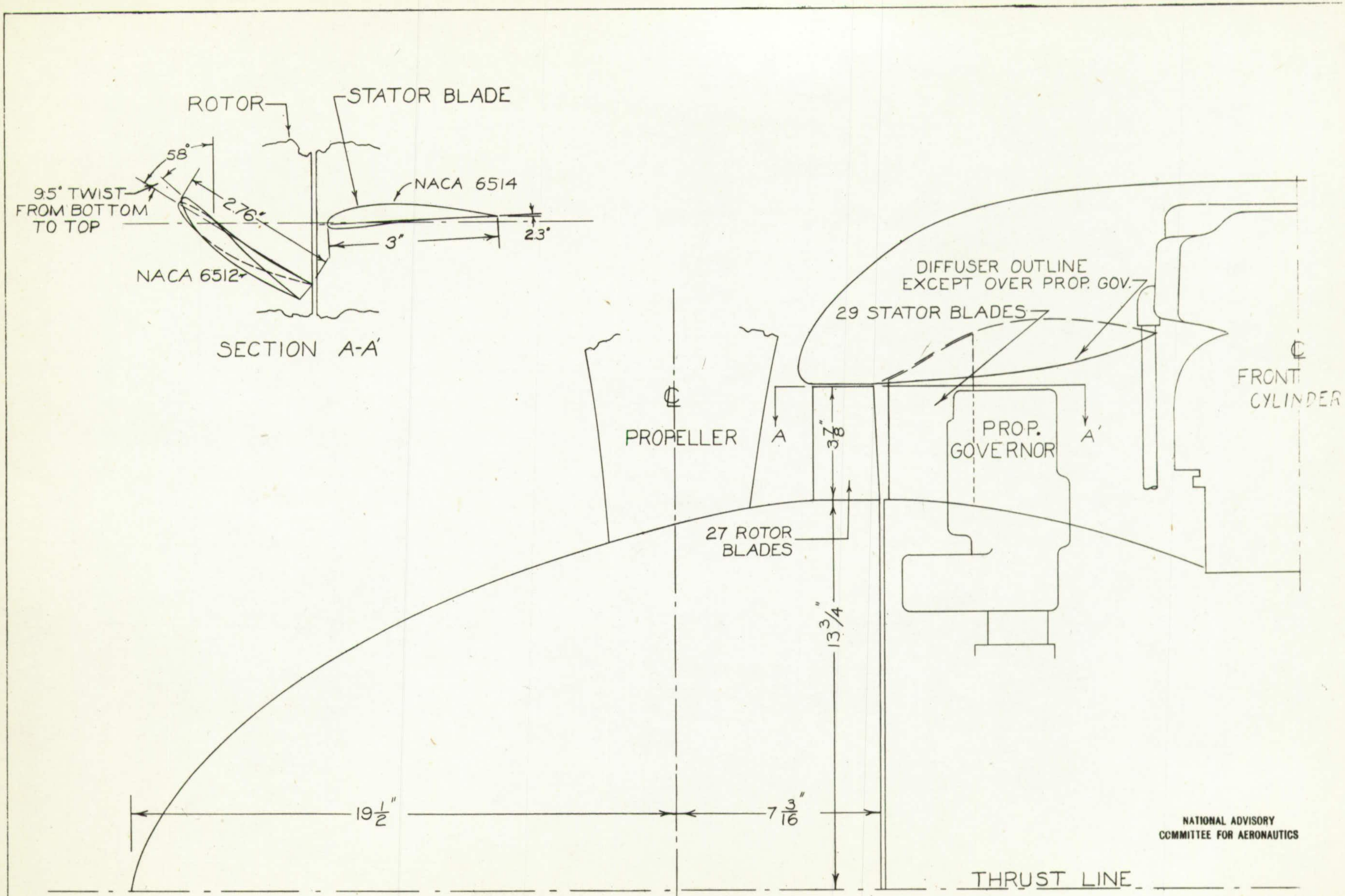


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FIGURE 43. - SPINNER BLOWER INSTALLATION WITH STATOR VANES.

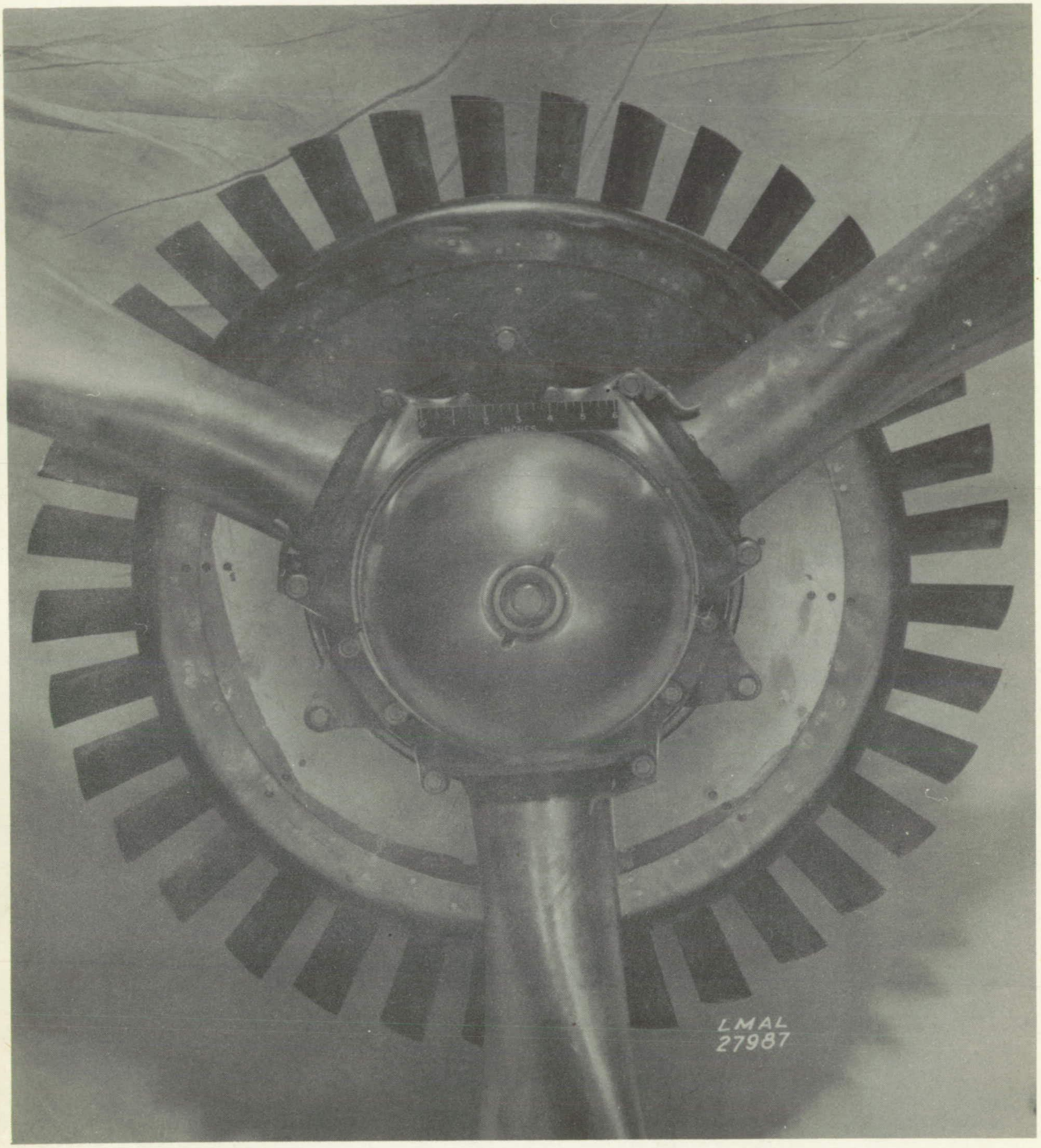

Figure 44.- Dishpan blower, front view.

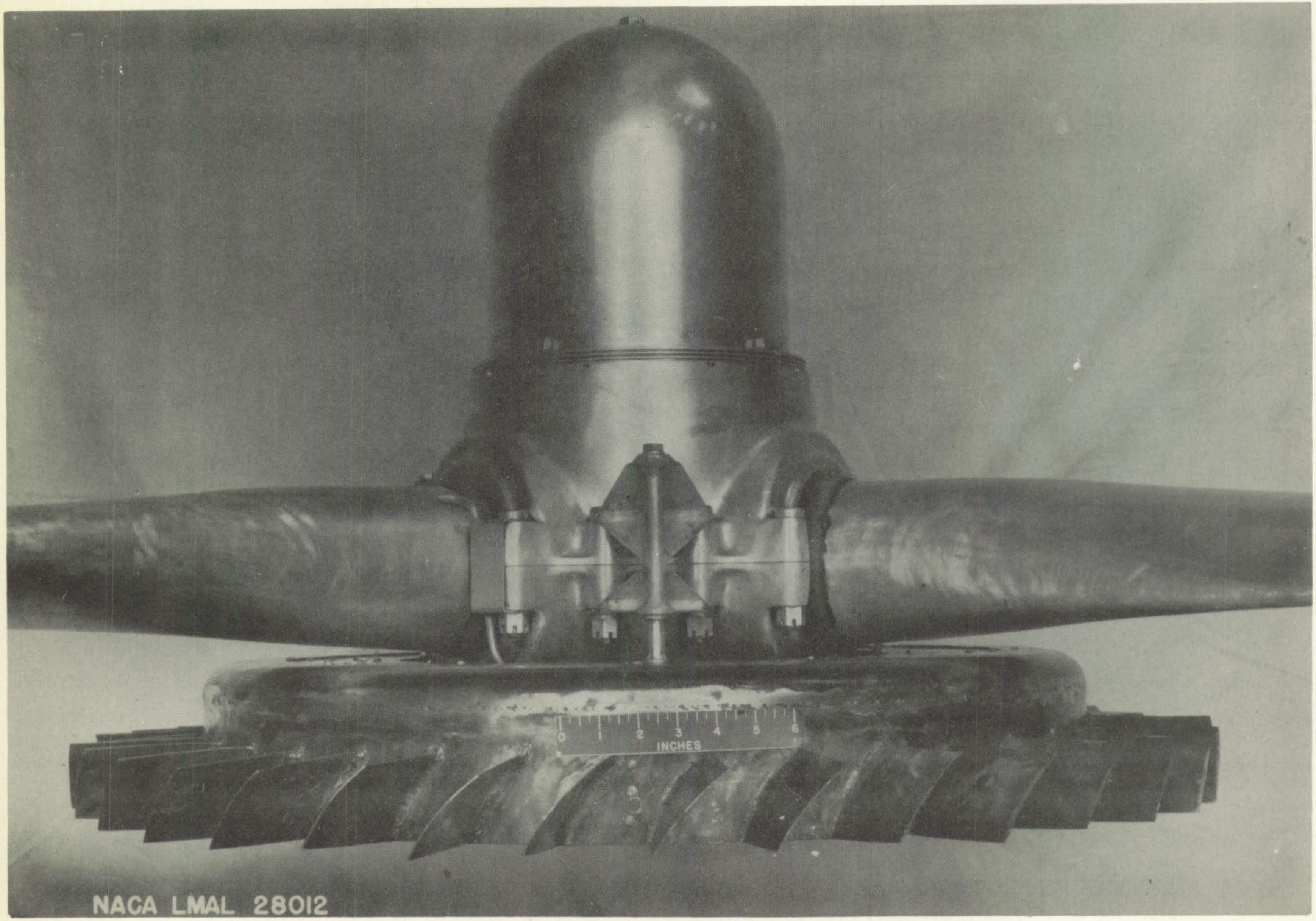

Figure 45.- Dishpan blower, side view.

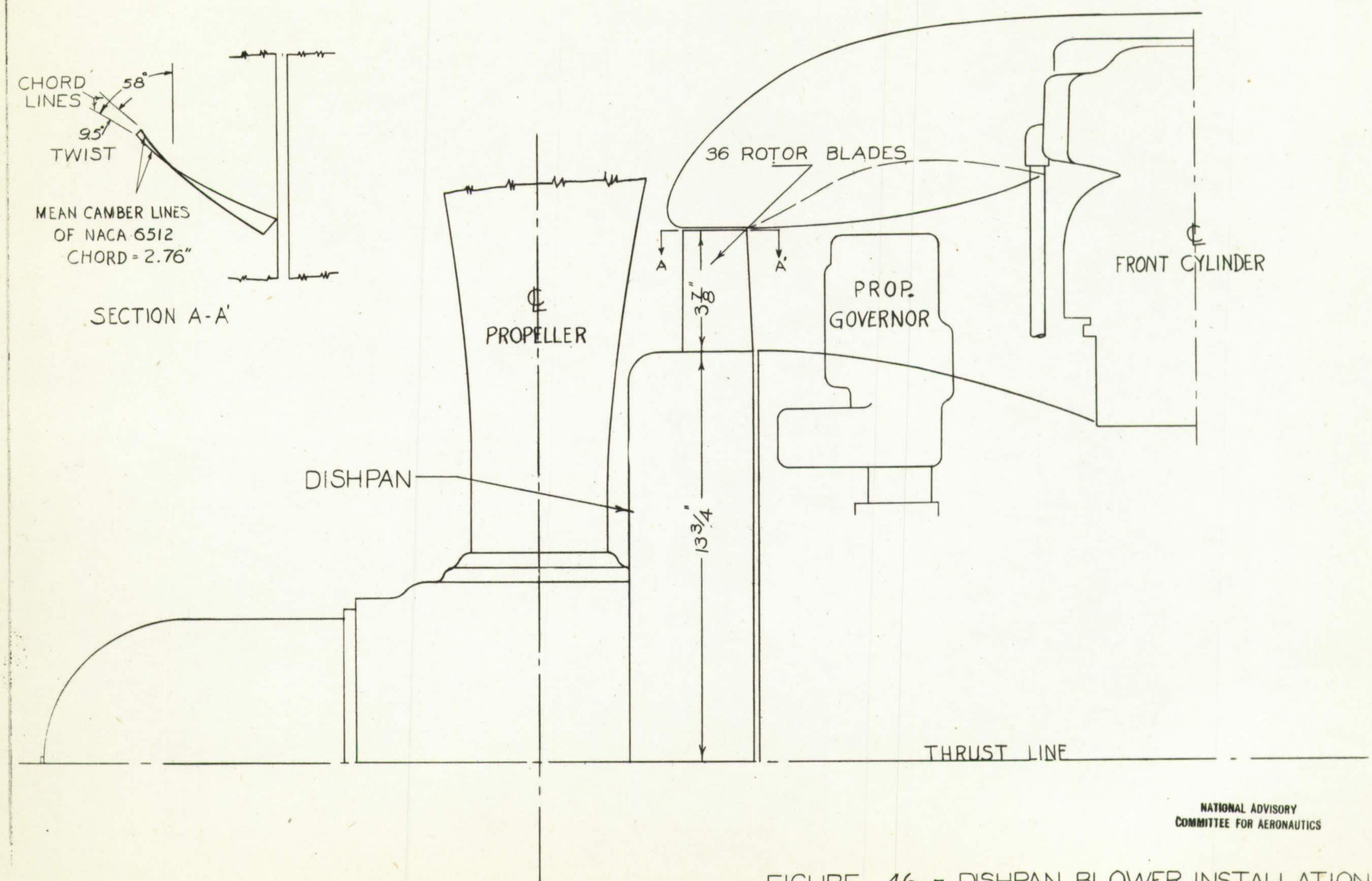

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FIGURE 46. - DISHPAN BLOWER INSTALLATION.

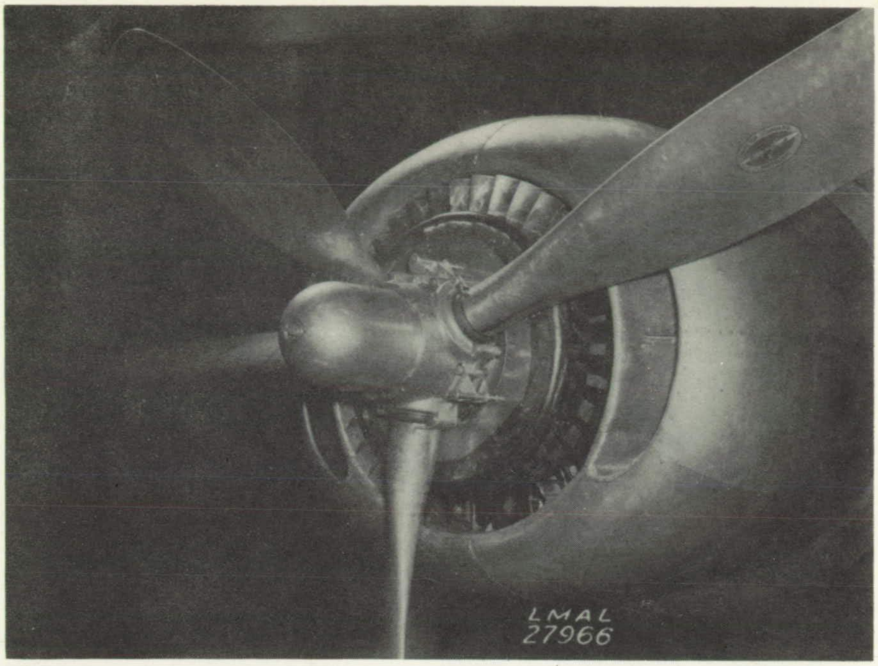


Figure 47.- Dishpan blower mounted on nacelle.

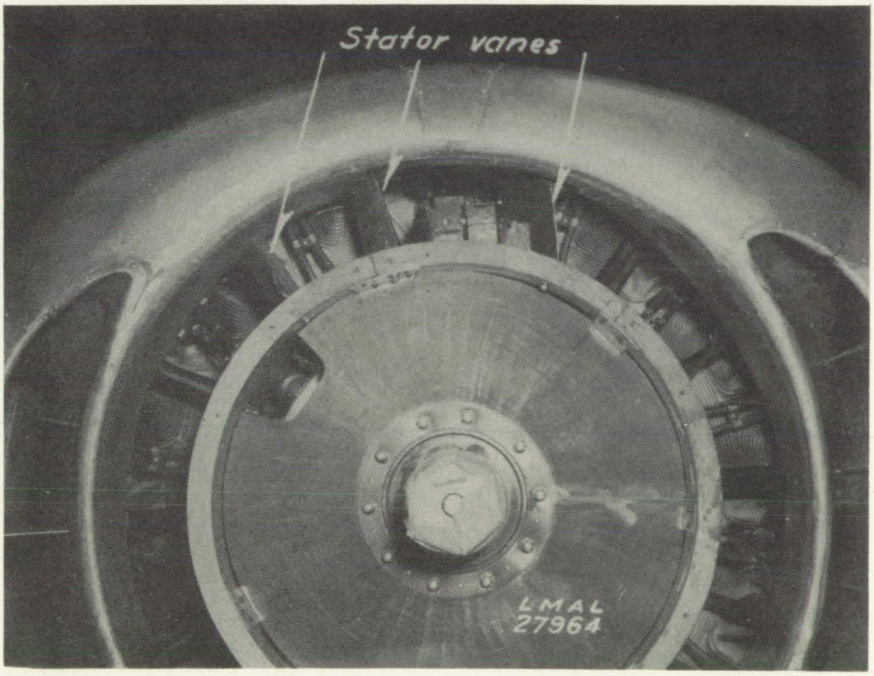
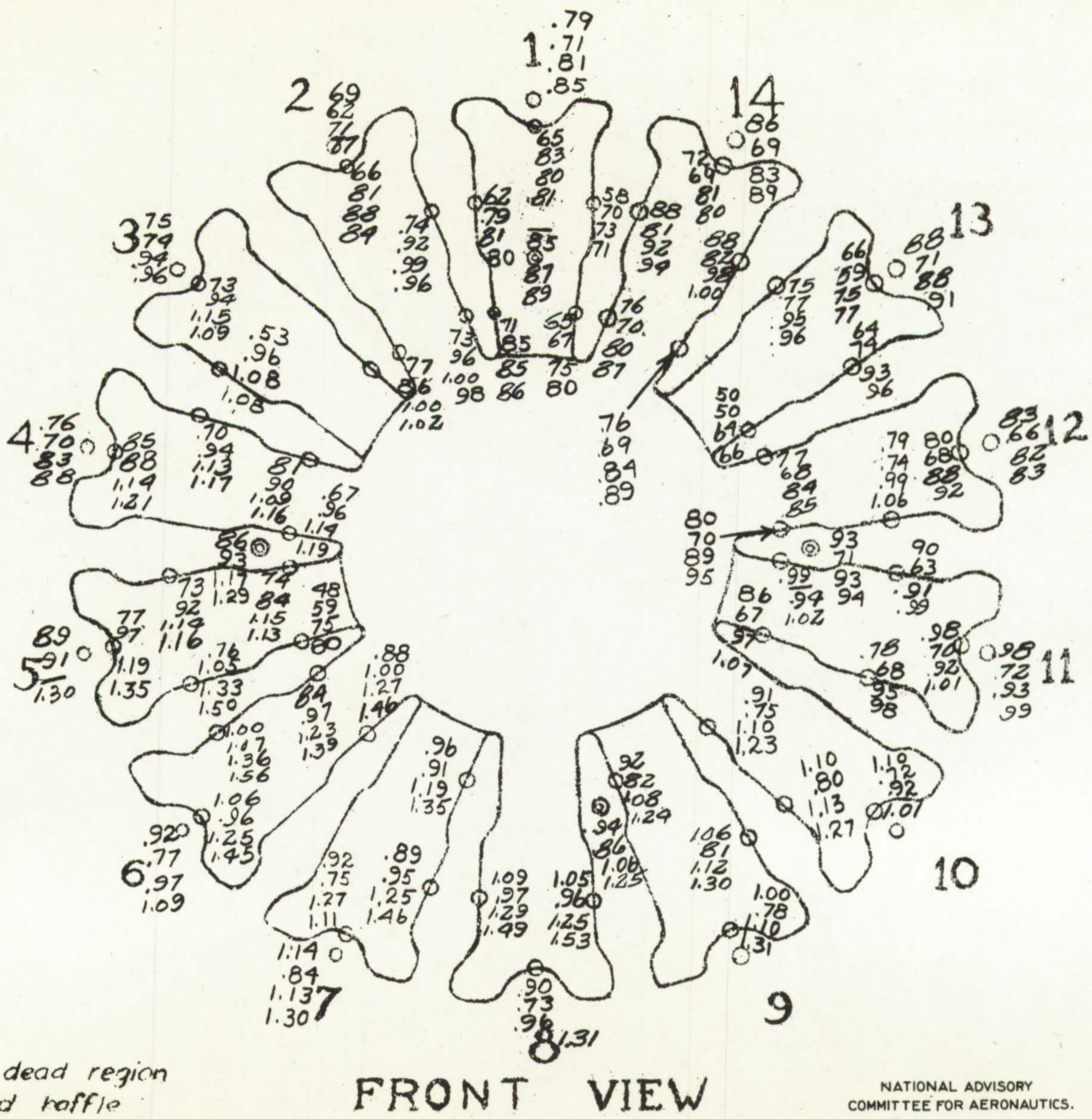


Figure 48.- Stator vanes used with dishpan blower.

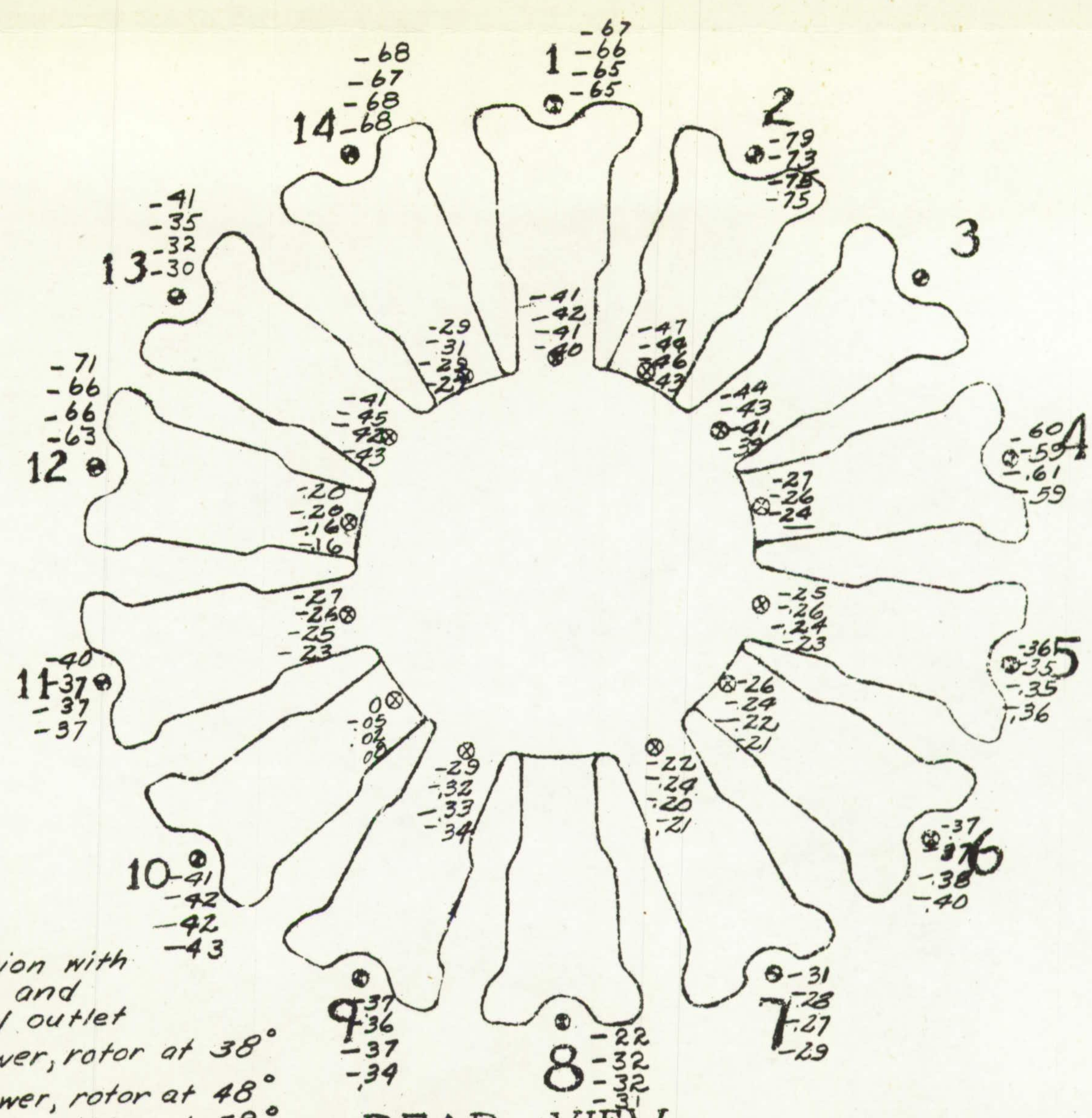


○ Total head

⊗ Static

● Total head in dead region behind head baffle

◎ Shielded total head



(a.) Basic condition with 10 inch flap and modified cowl outlet

(b.) Spinner blower, rotor at 38°

(c.) Spinner blower, rotor at 48°

(d.) Spinner blower, rotor at 58°

FIGURE 49. - ENGINE PRESSURE DISTRIBUTION FOR THE B-24D ENGINE-NACELLE INSTALLATION WITH THE MODIFIED COWL OUTLET, THE 20-INCH COWL FLAP, AND THE SPINNER BLOWER; CLIMB.

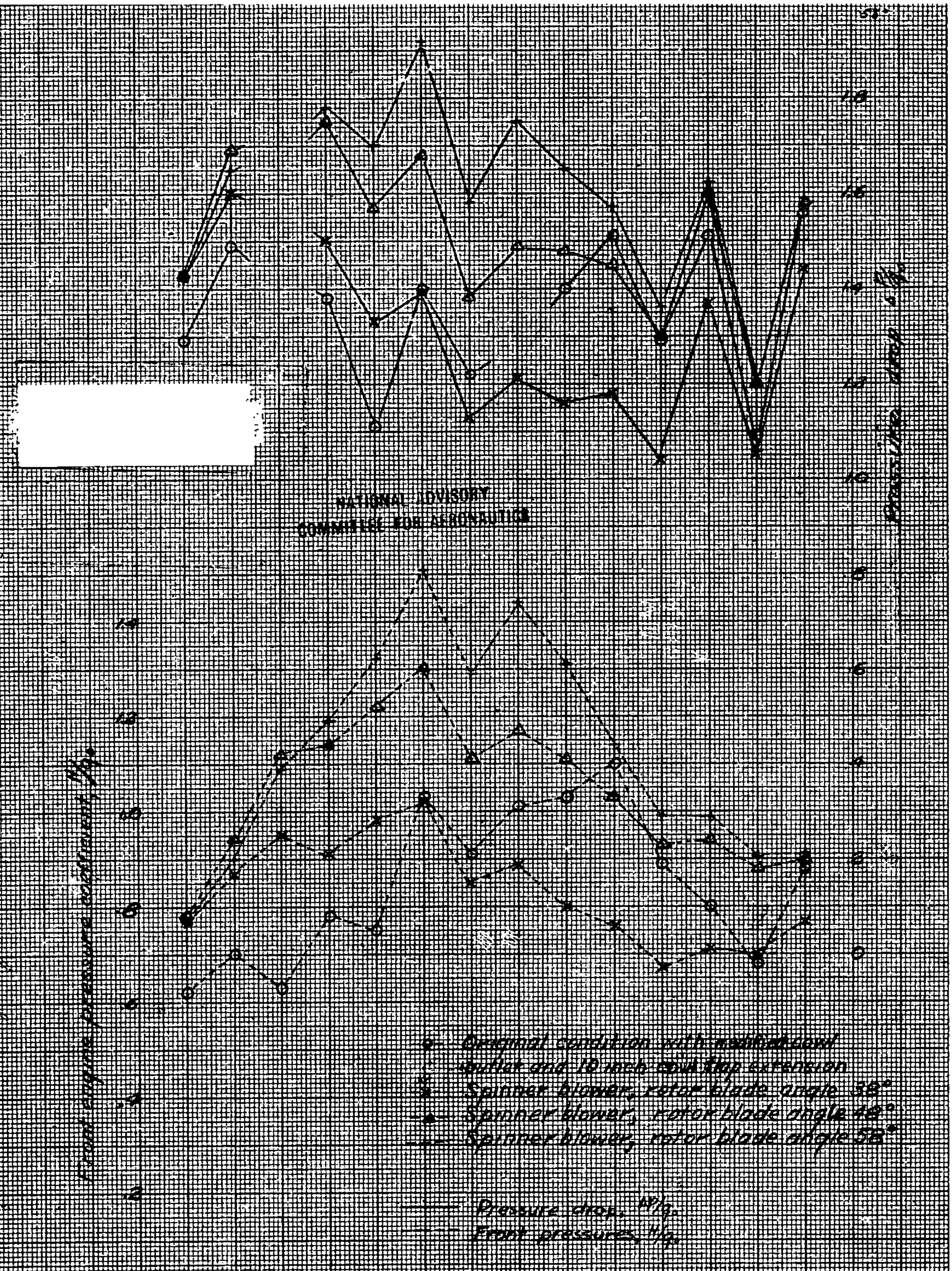


Figure 50. - Variation of the front engine baffle pressures and the pressure drop with the spinner blower installation at three rotor blade angles; climb altitude, hmax.

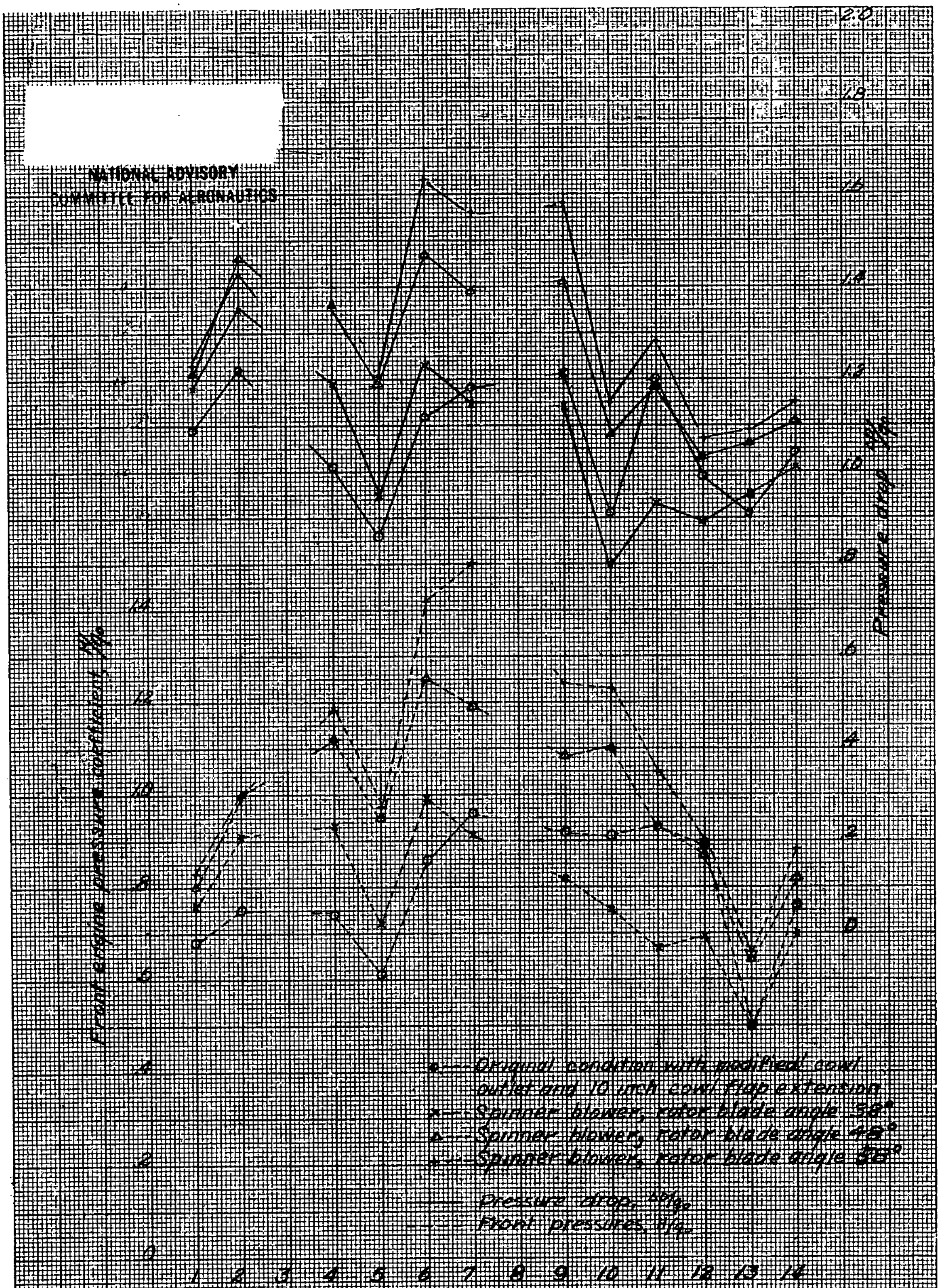
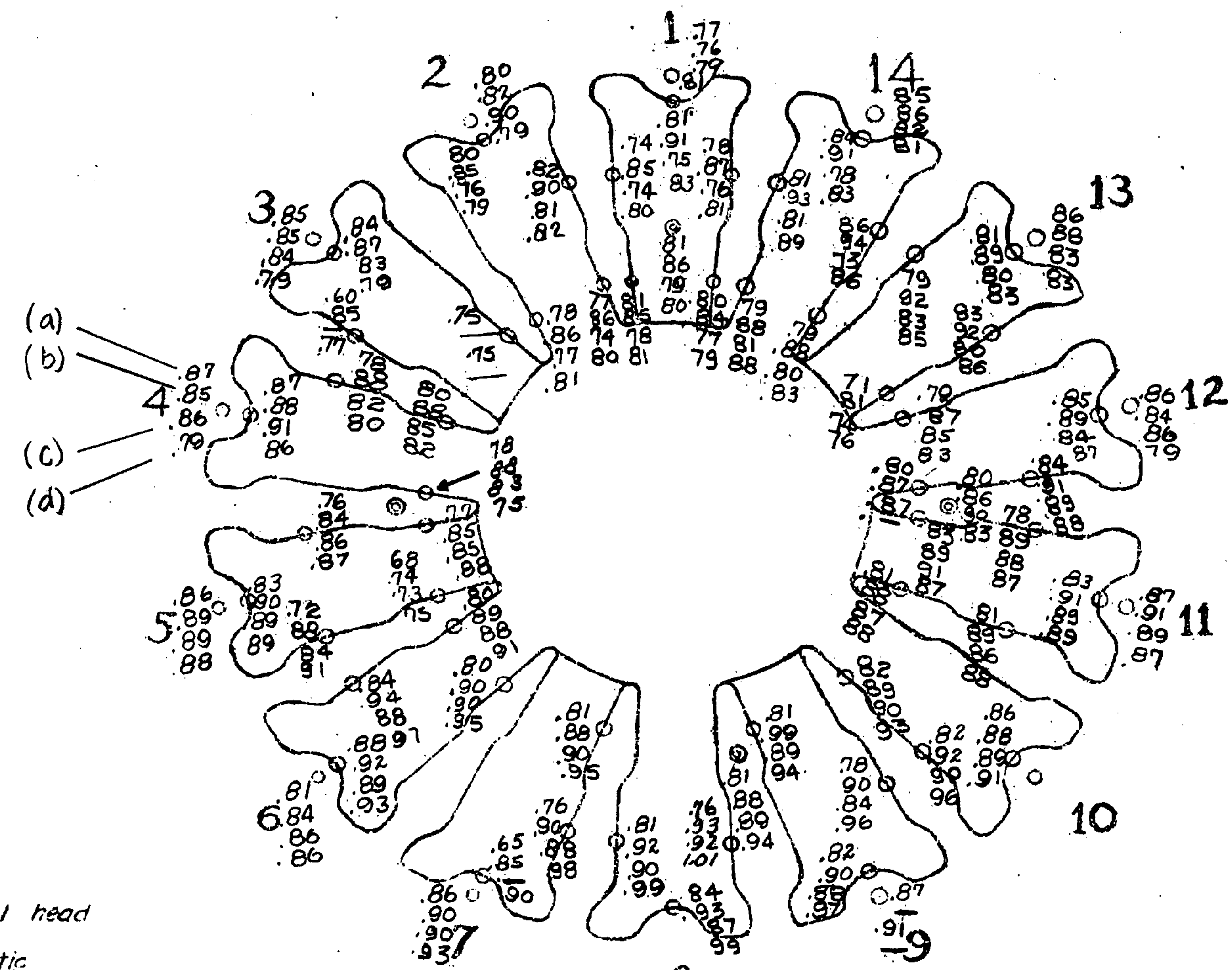


Figure 51. - Variation of the front baffle pressures and the pressure drops with the spinner blower installation at three rotor blade angles; climb attitude; barrels



FRONT VIEW

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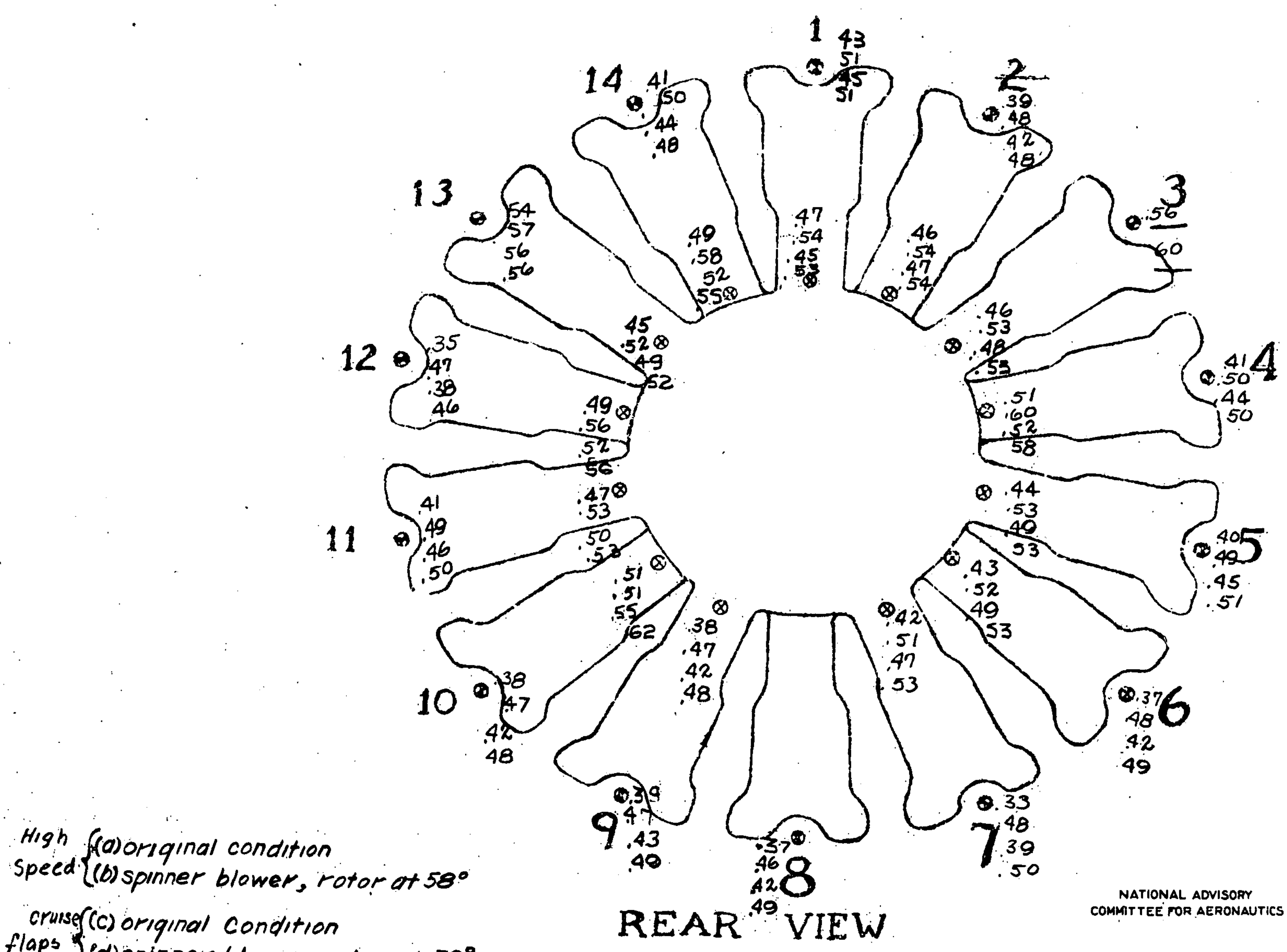

REAR VIEW

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FIGURE 52. - ENGINE PRESSURE DISTRIBUTION FOR THE B-24D ENGINE-NACELLE INSTALLATION WITH THE MODIFIED COWL OUTLET, THE 20-INCH COWL FLAP, AND THE SPINNER BLOWER; HIGH SPEED AND CRUISING.

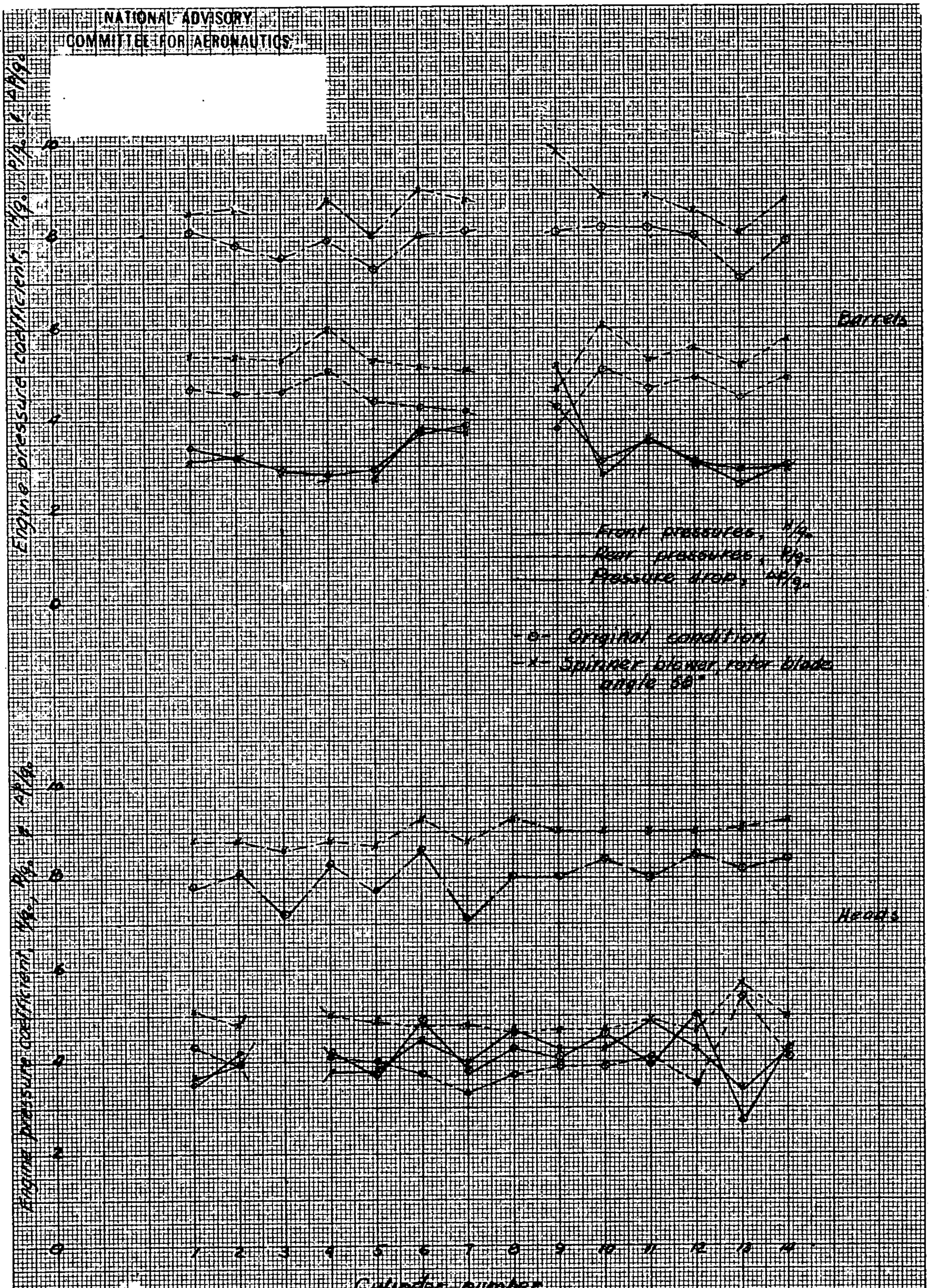


Figure 53. - Variation in the front and rear engine pressures and the pressure drop due to the spinner blower; high-speed attitude.

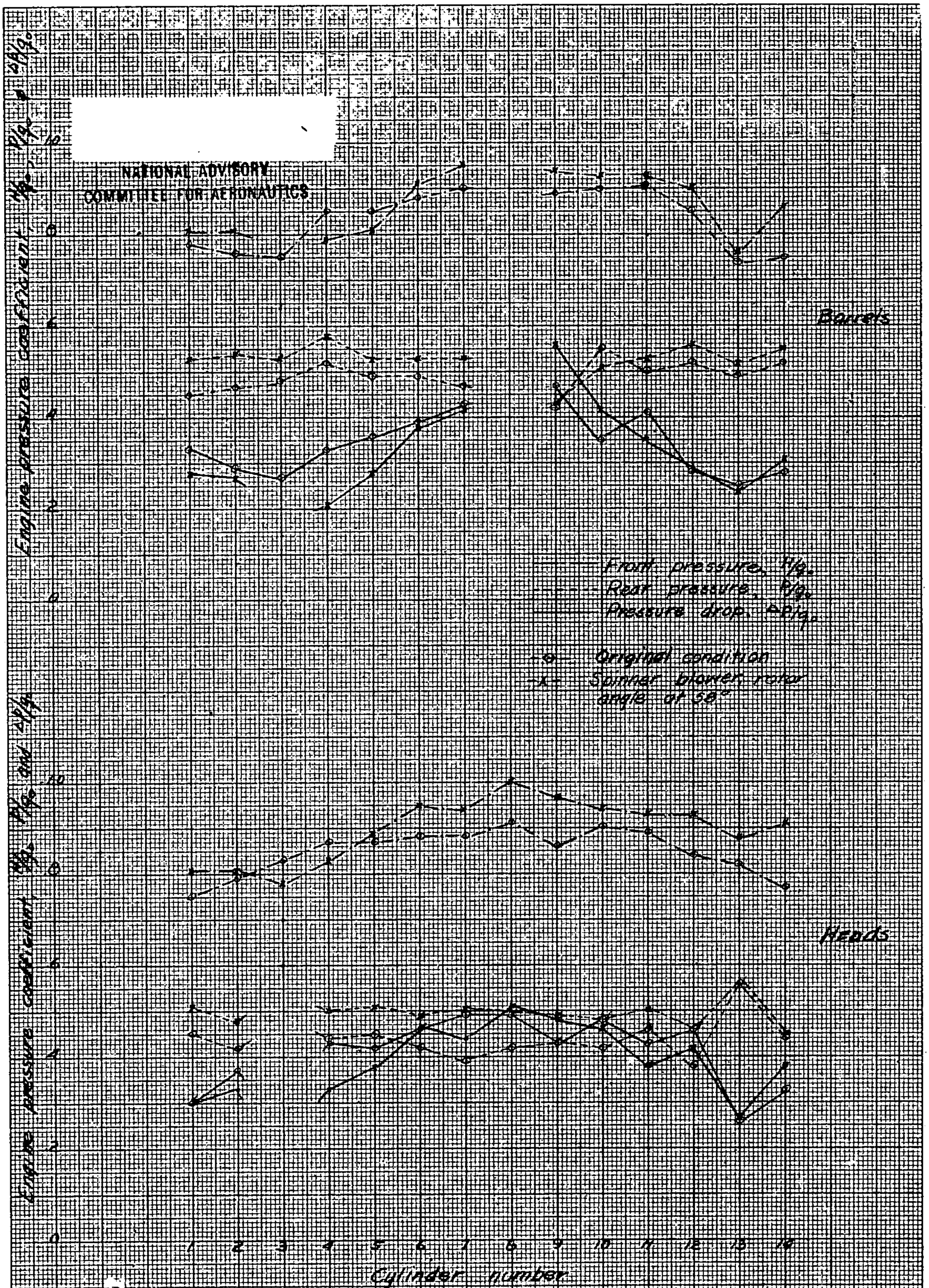
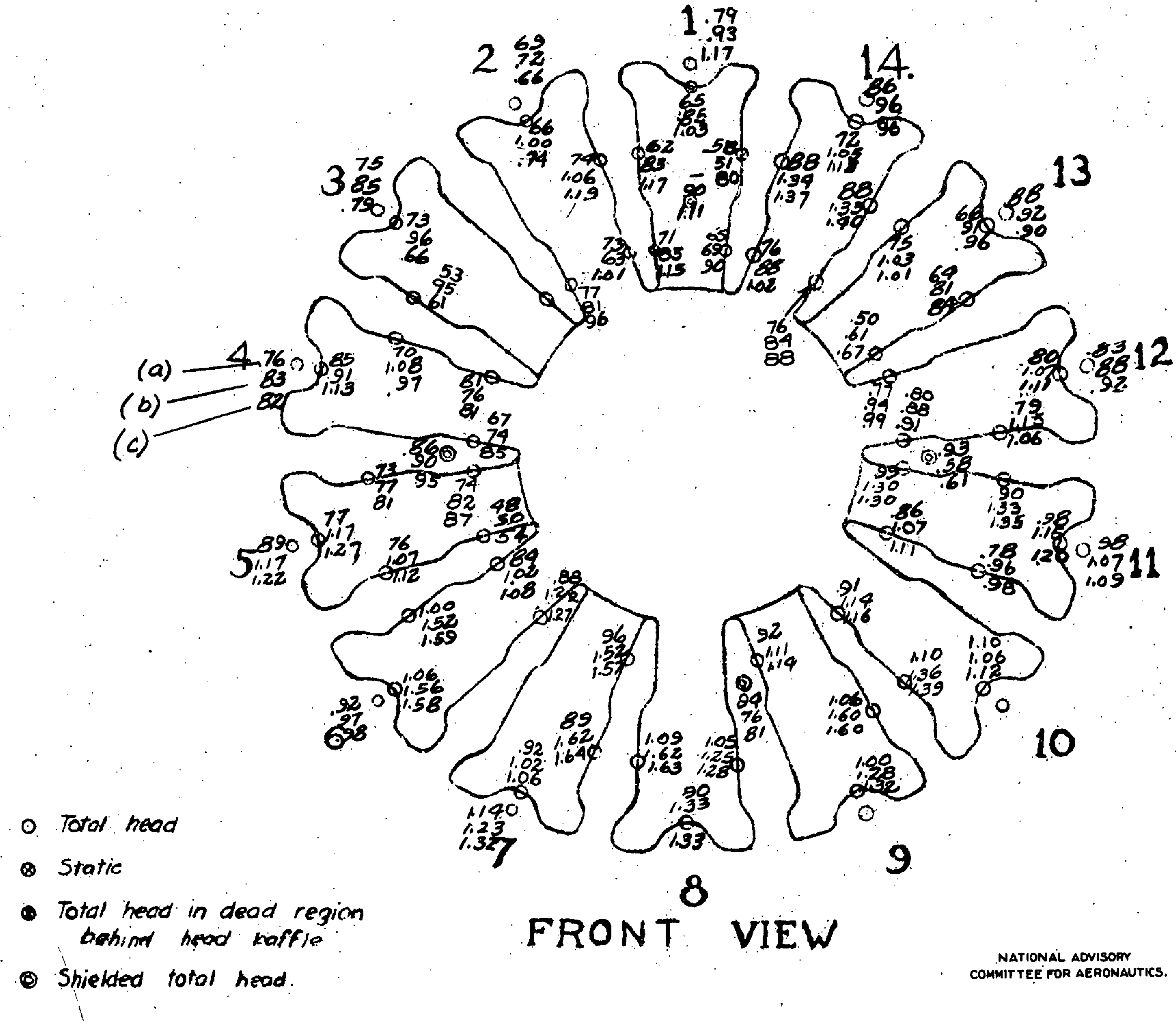


Figure 54. - Variation in the front and rear engine pressures and the pressure drop due to the spinner blower; cruising attitude.



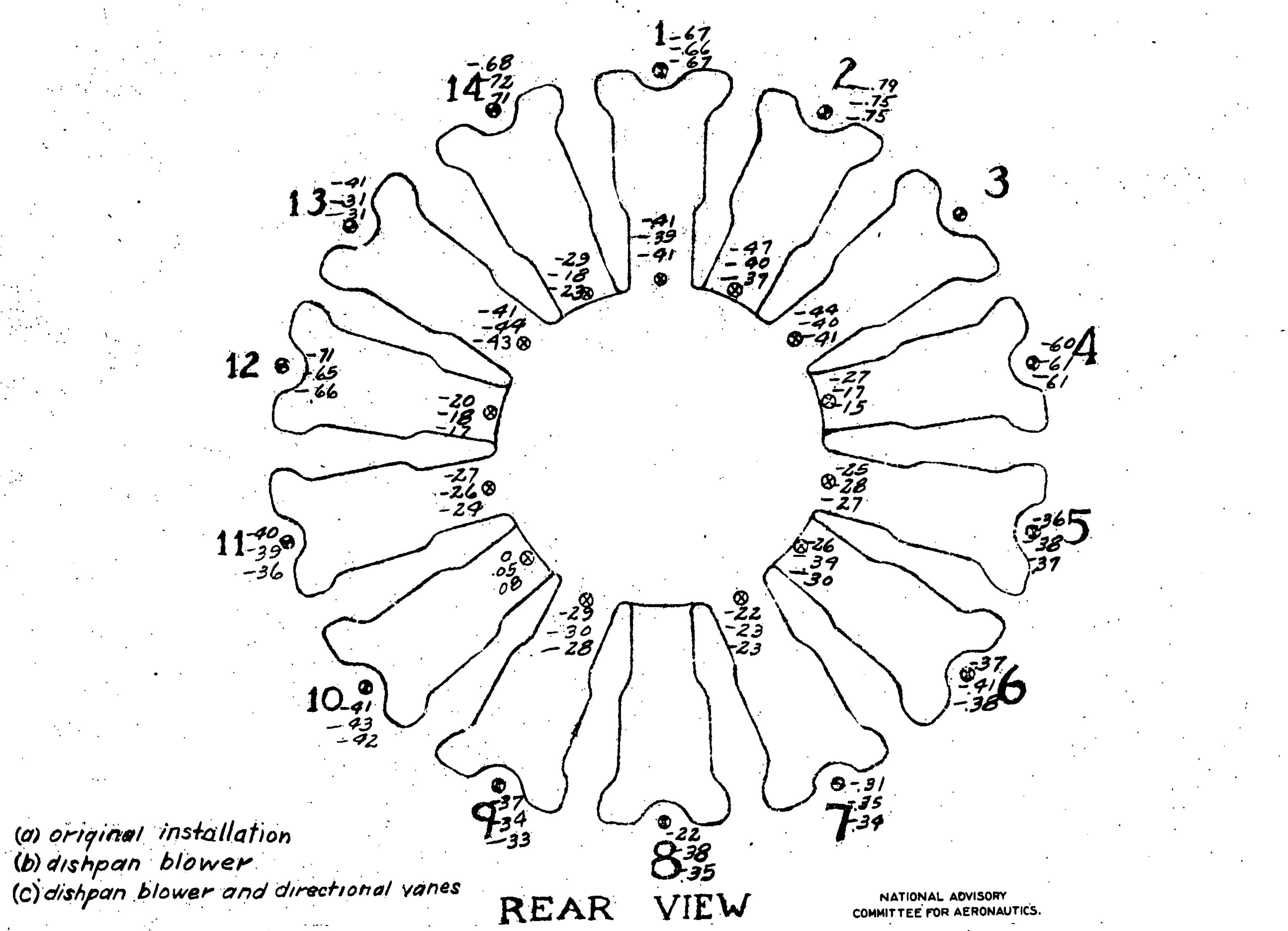


FIGURE 55. - ENGINE PRESSURE DISTRIBUTION FOR THE B-24D ENGINE-NACELLE INSTALLATION WITH THE MODIFIED COWL OUTLET, THE 20-INCH COWL FLAP, AND THE DISHPAN BLOWER; CLIMB ATTITUDE.

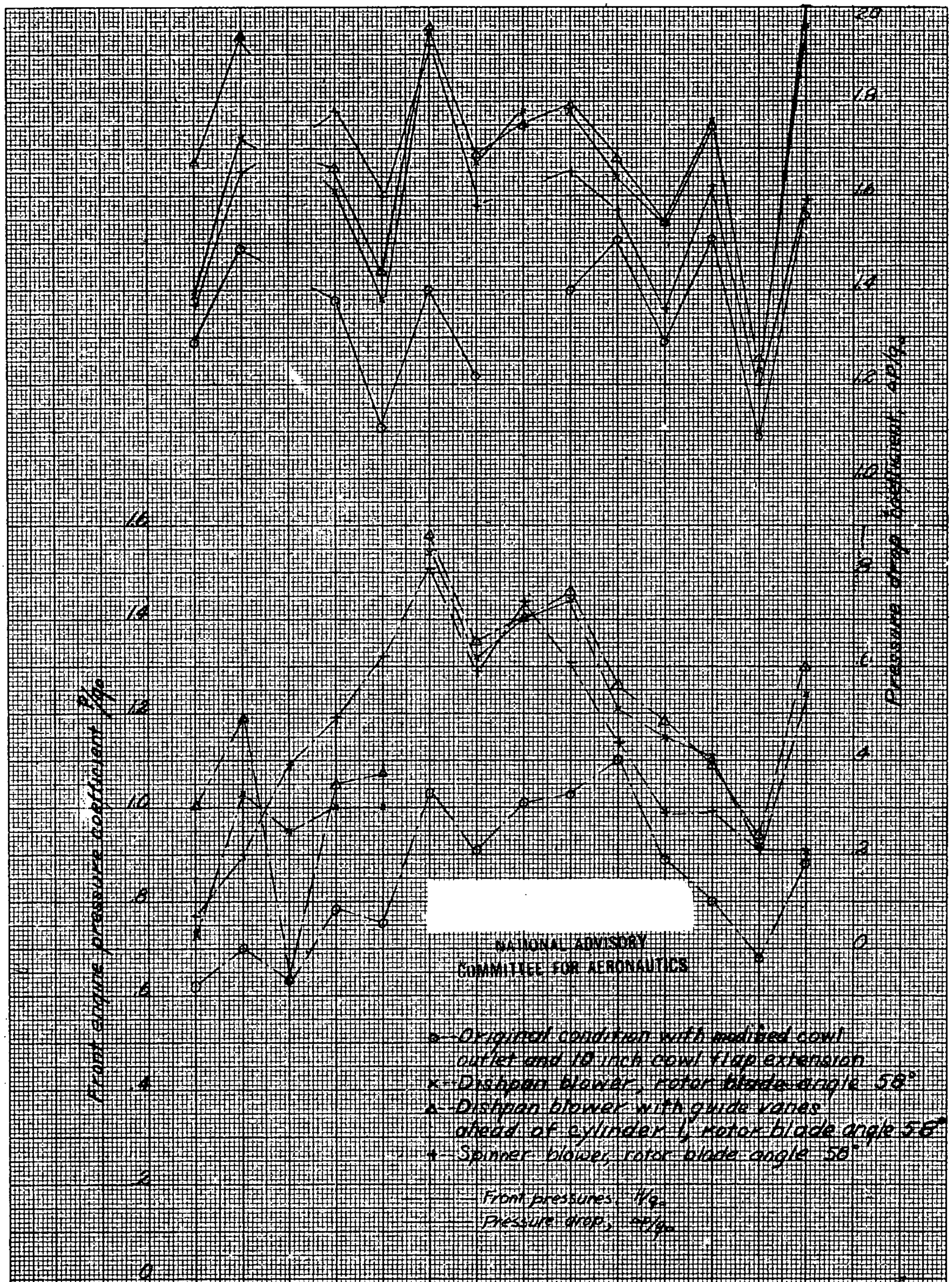


Figure 56. - Variation of front engine baffle pressures and the pressure drops across the heads in the climb condition with the Dishpan blower, with and without guide vanes ahead of cylinder 1. Climb attitude

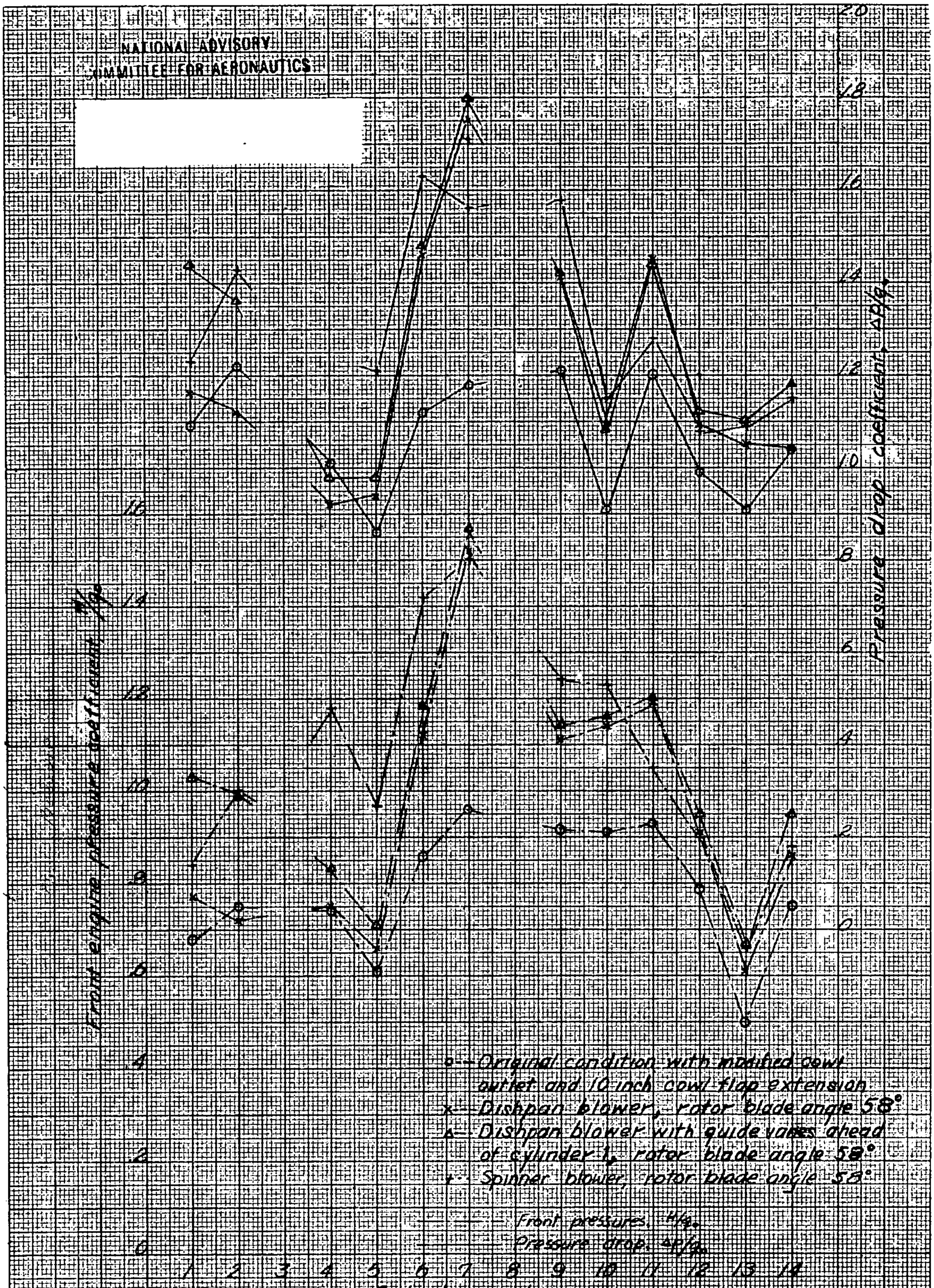


Figure 57. - Variation of front engine baffle pressures and the pressure drops across the barrels in the climb condition with the dishpan blower, with and without guide vanes ahead of cylinder 1.

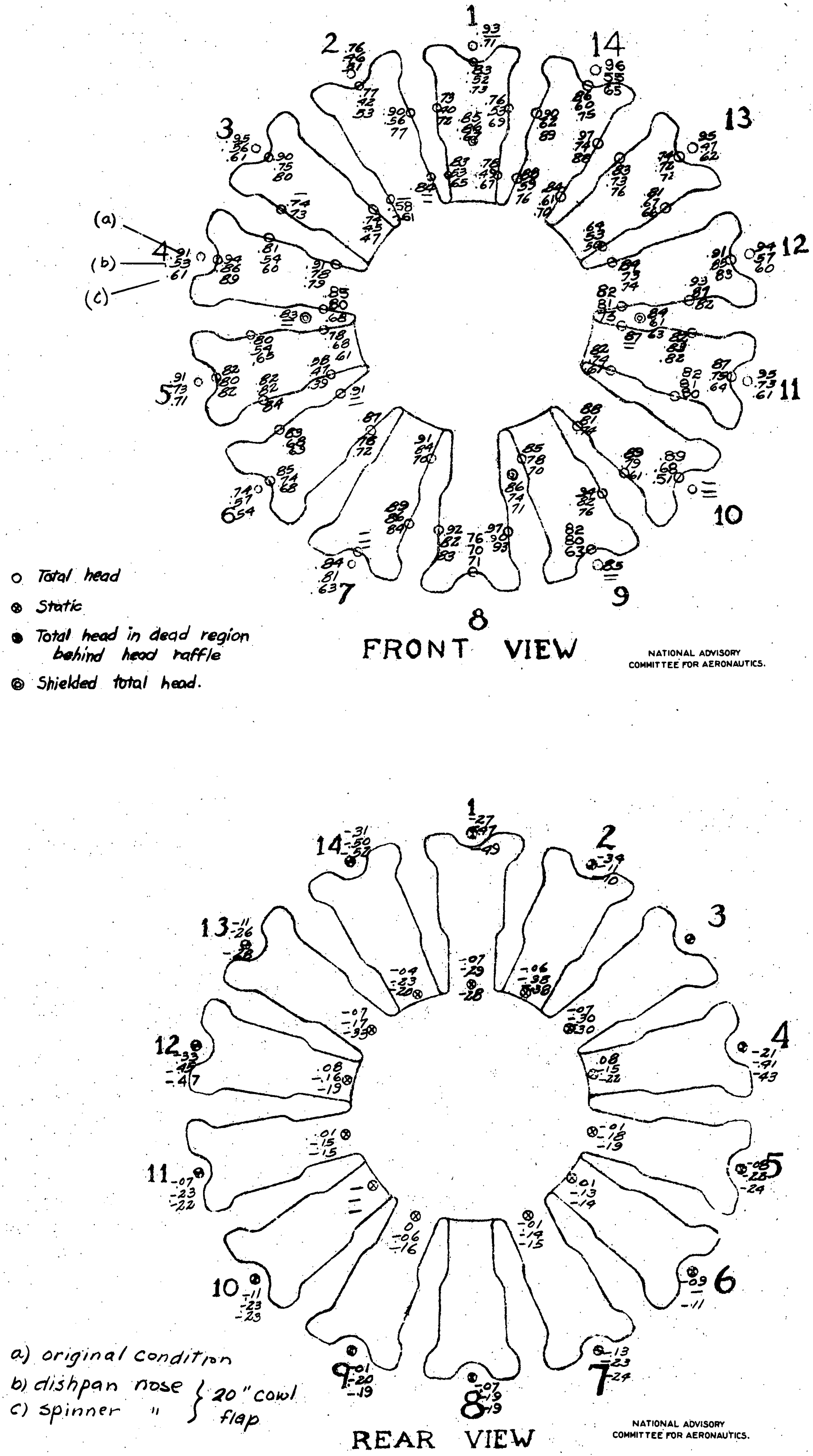


FIGURE 58. - POWER-OFF ENGINE PRESSURE DISTRIBUTION FOR THE B-24D ENGINE-NACELLE INSTALLATION WITH THE MODIFIED COWL OUTLET, THE 20-INCH COWL FLAP, AND SPINNER AND DISHPAN NOSE; CLIMB.

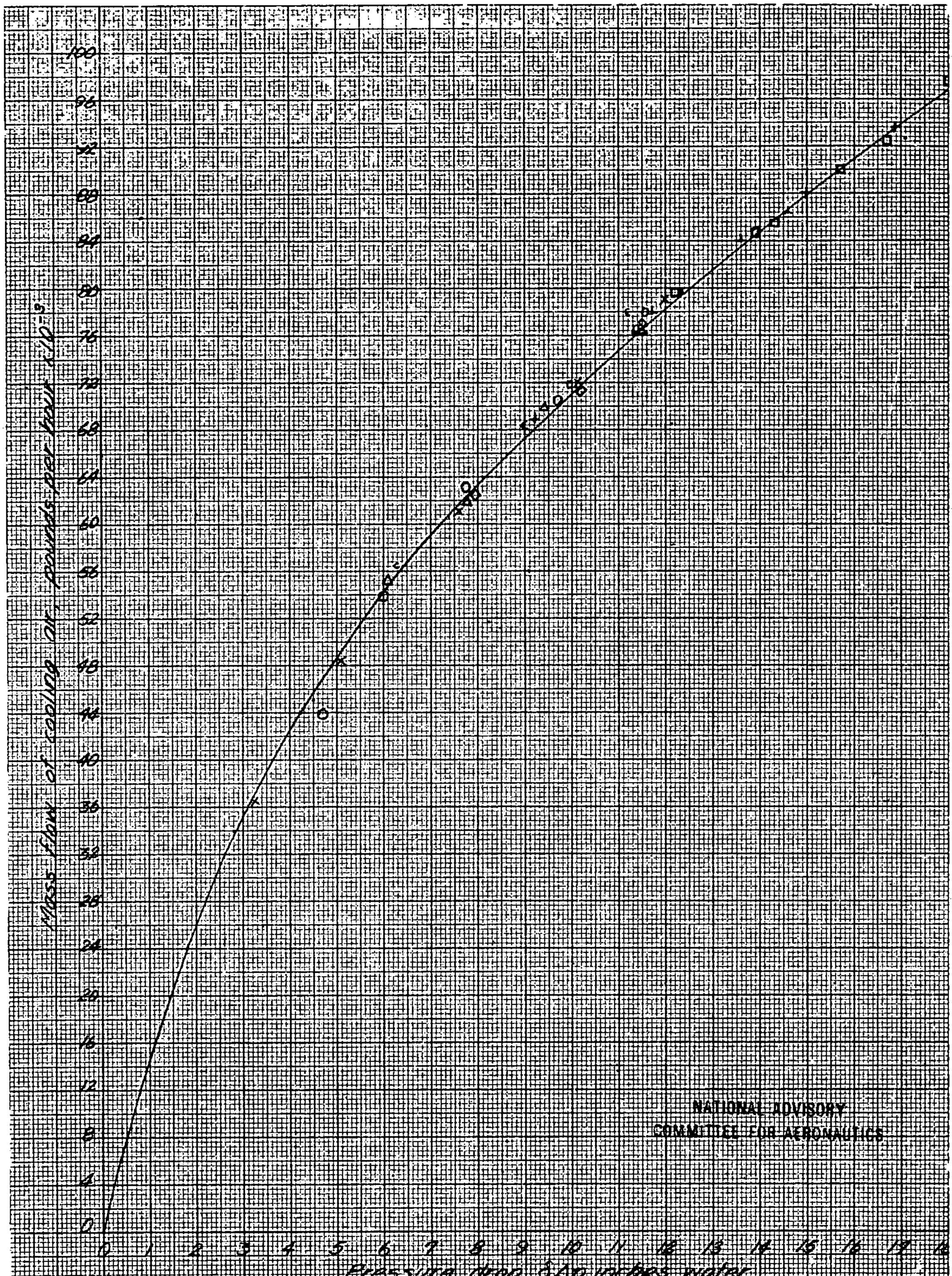


Figure 59. - Variation of mass flow of cooling air through the engine with average pressure drop as measured with standard Army buttons. Test-stand data obtained by Pratt & Whitney.

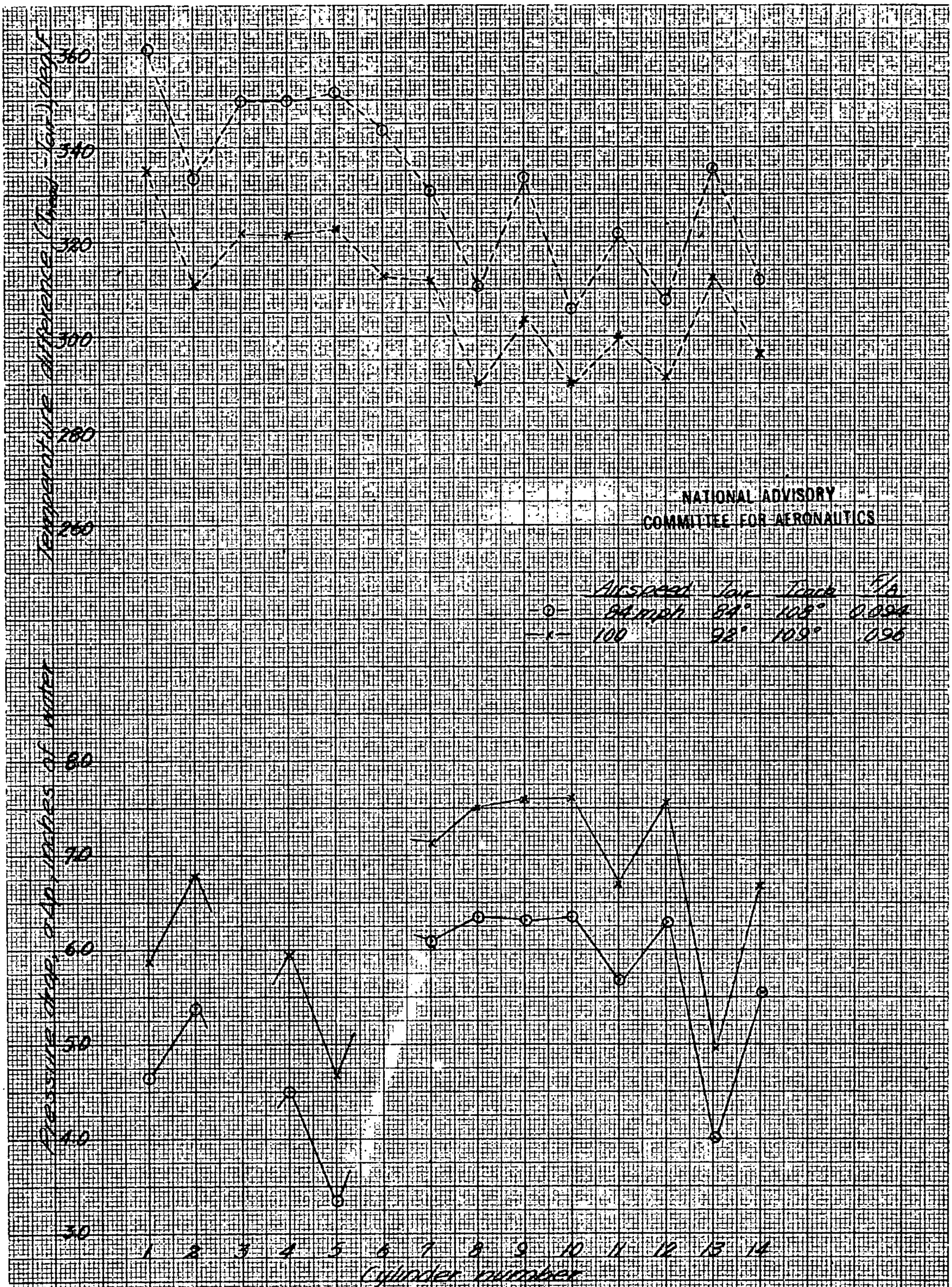


Figure 60. - Correlation between the head temperatures and the pressure drops; approximately 750 horsepower.

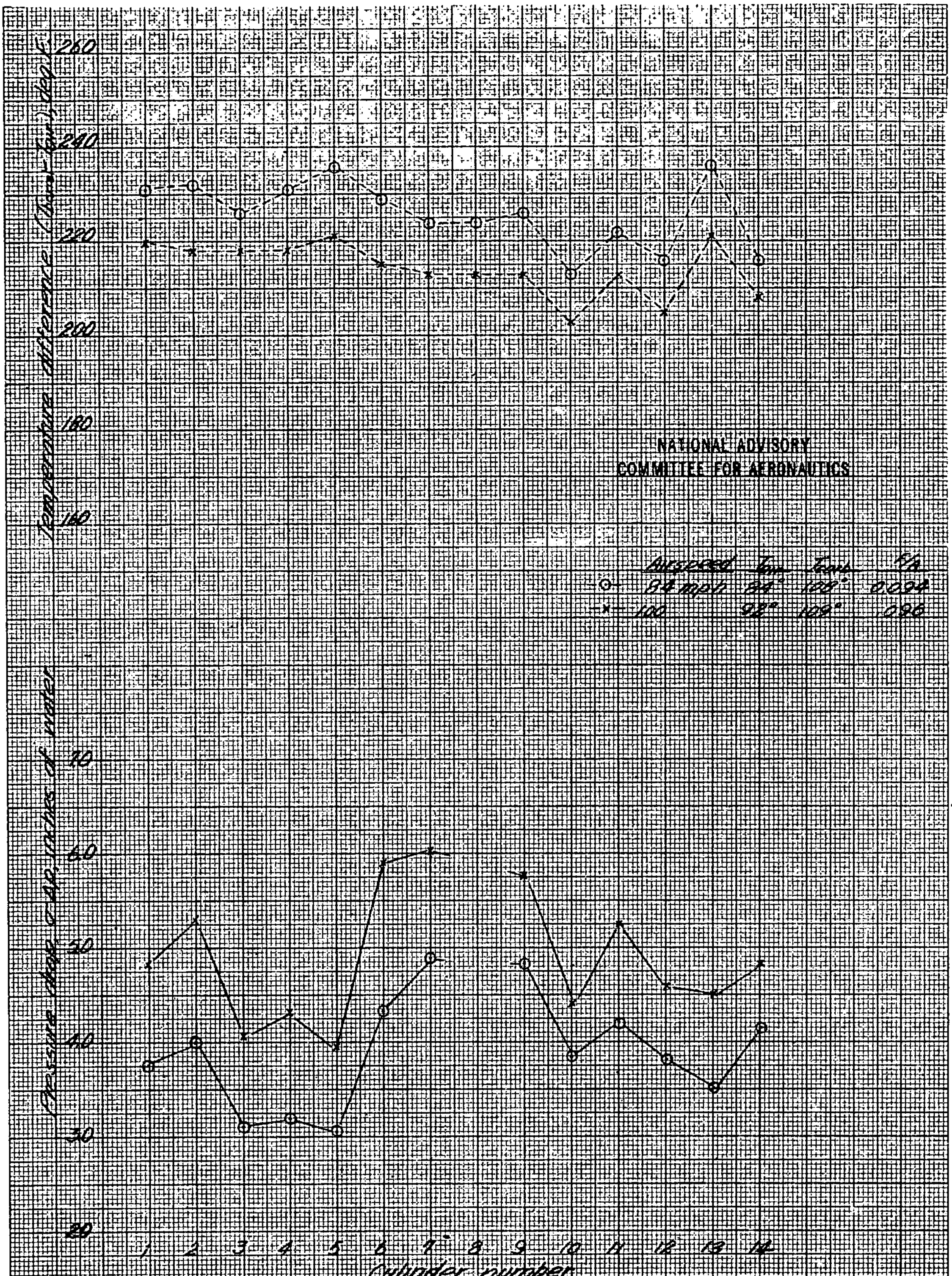


Figure 61. - Correlation between the barrel temperature and the pressure drops; approximately 750 horsepower.

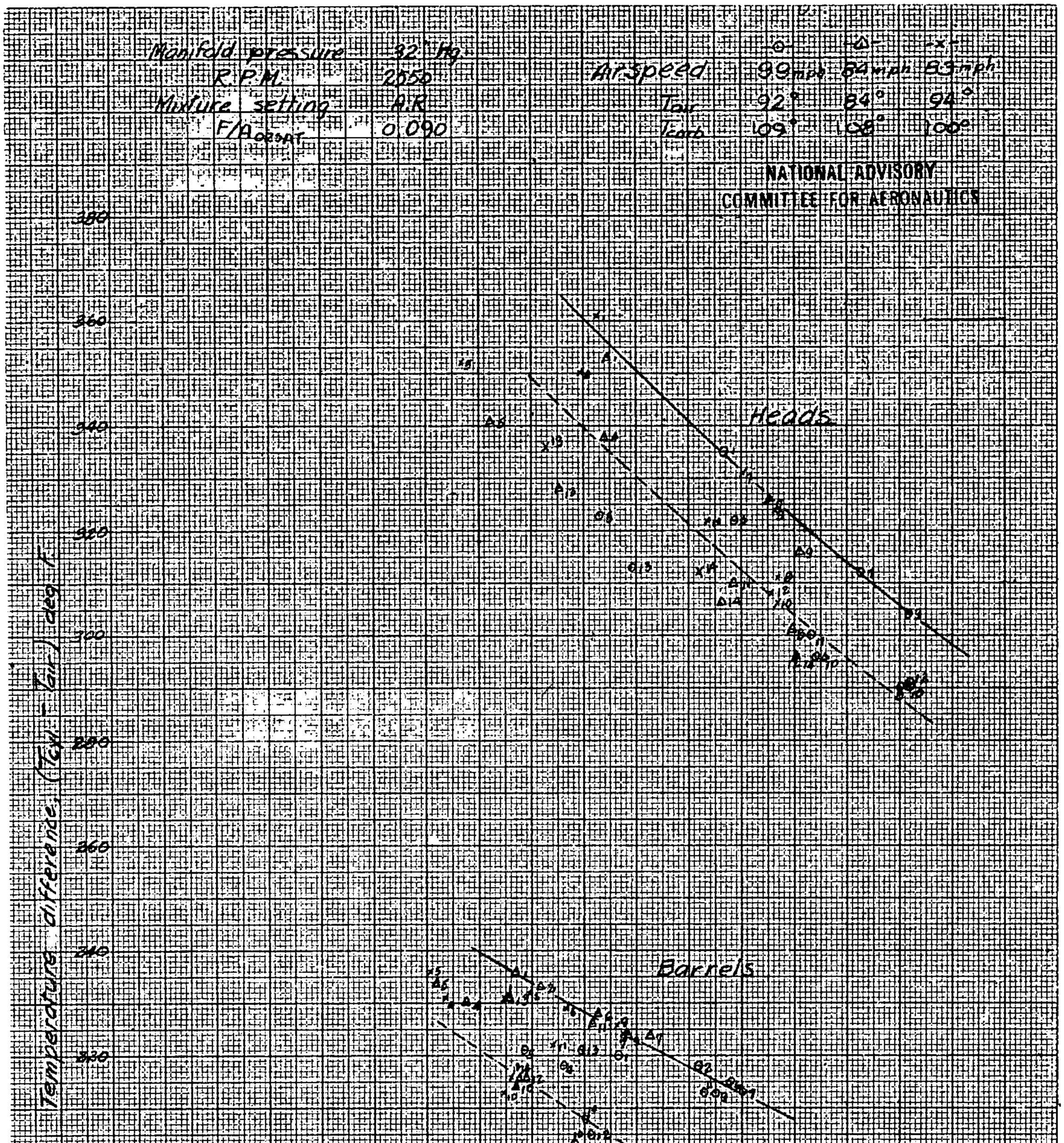


Figure 62. - Variation of cylinder temperatures with pressure drop; 800 horsepower; 20-inch cowl flaps full open.

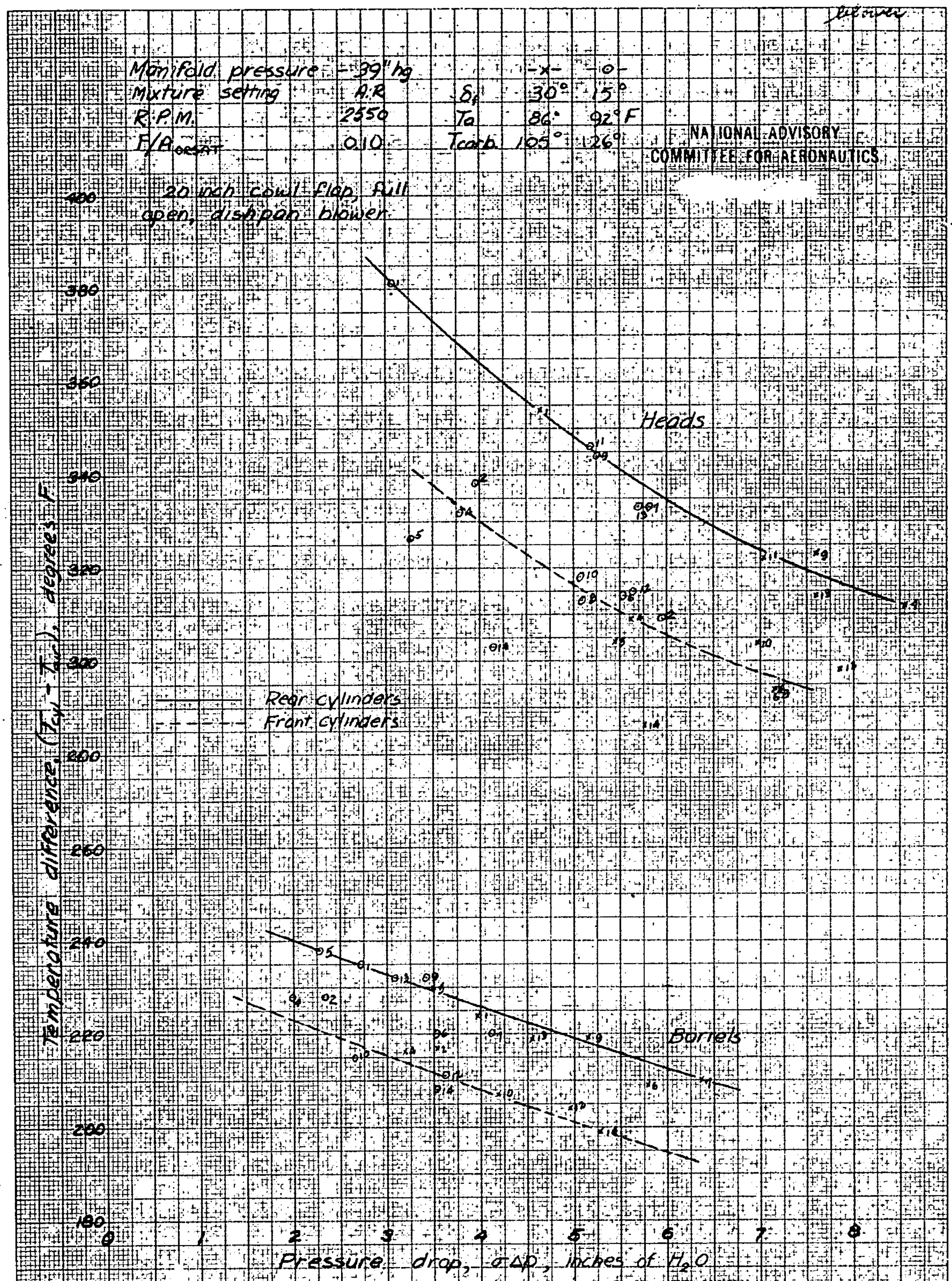


Figure 63. - Variation of cylinder temperatures with pressure drop; 1000 horsepower.

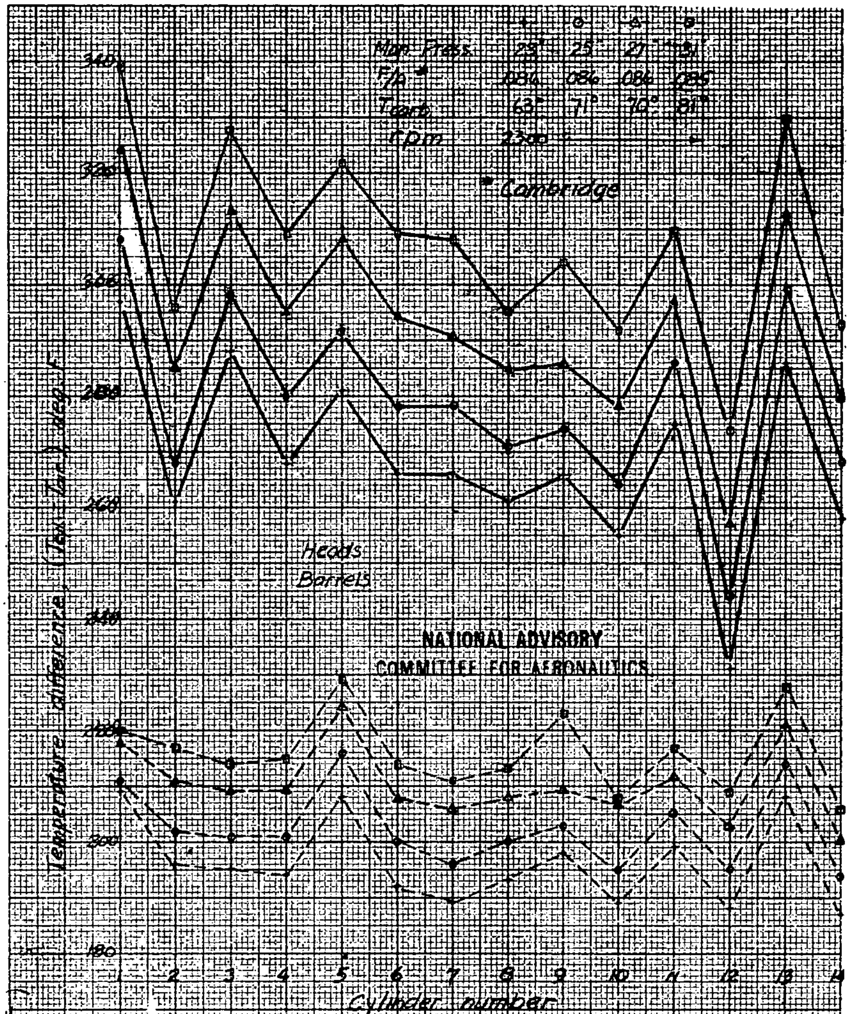


Figure 64. - Variation in cylinder temperatures with engine power.

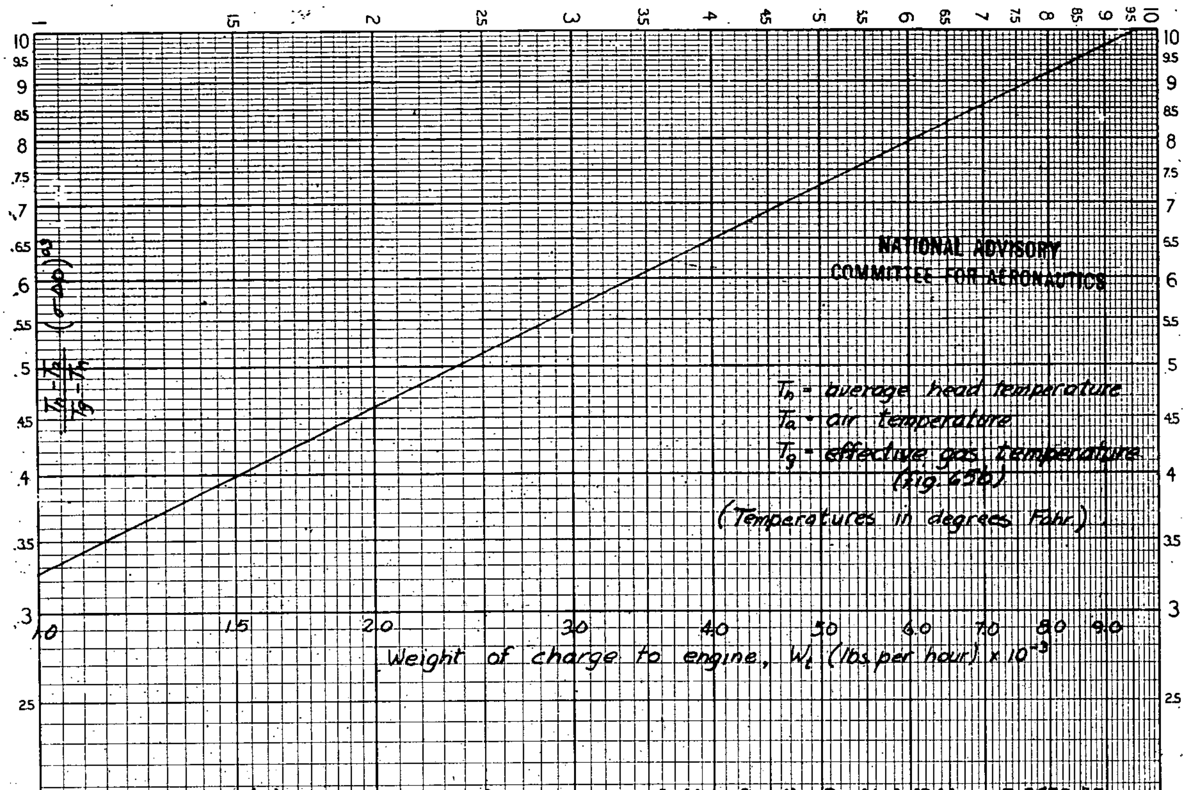


Figure 65(a). - Temperature and pressure correlation for the Pratt & Whitney R-1830-43 engine as determined from full-scale tunnel data obtained on the B-24D engine-nacelle installation.

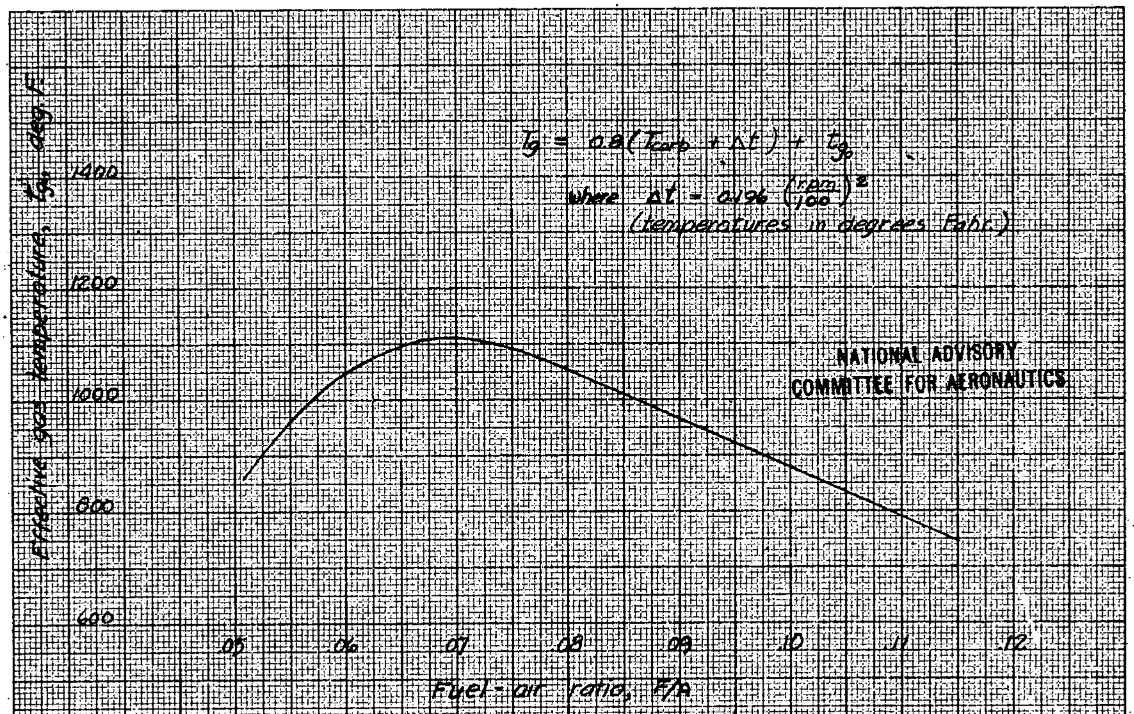


Figure 65(b). - Variation of effective gas temperature with fuel-air ratio used in conjunction with temperature and pressure correlation given in figure 65(a).

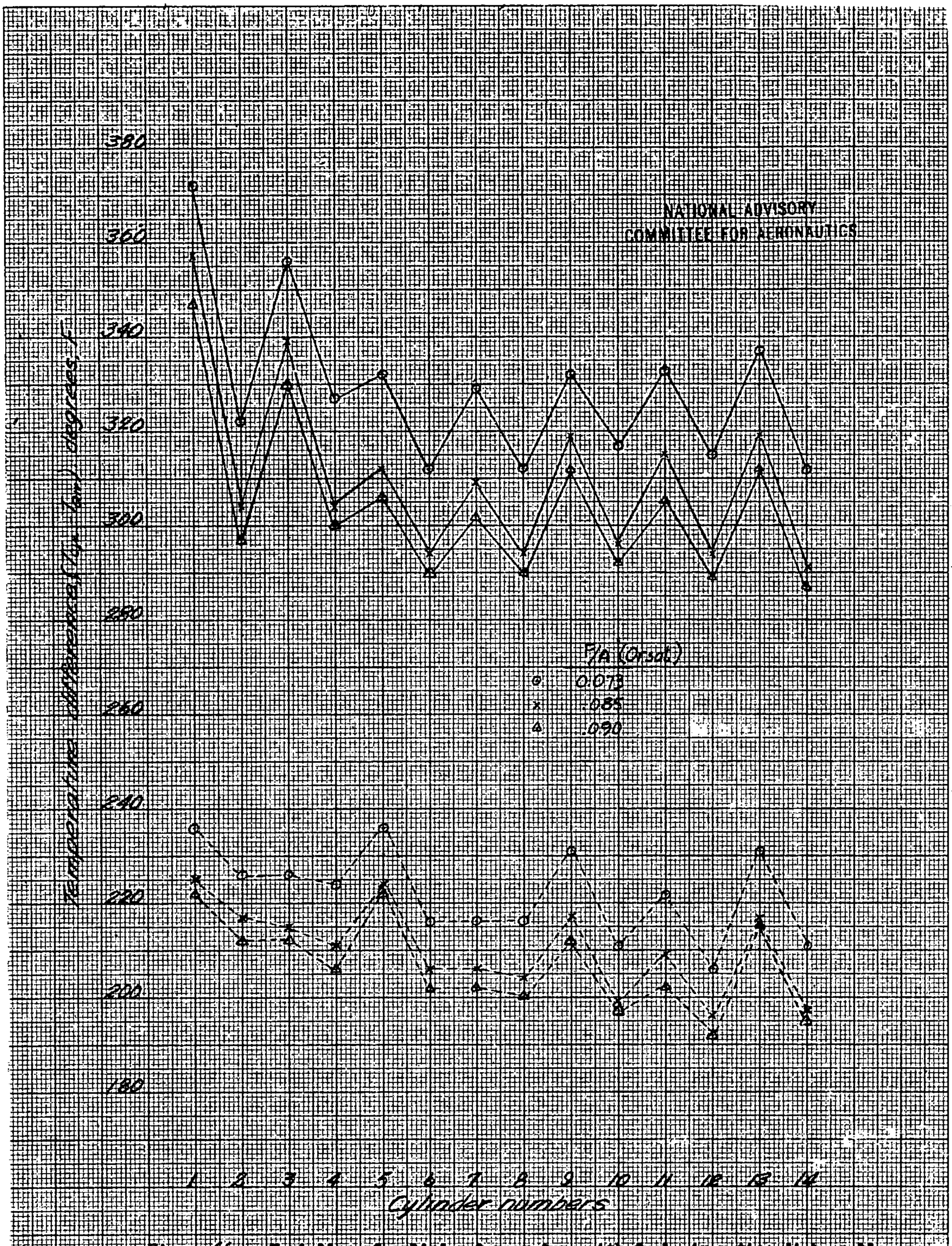


Figure 66. - Variation of cylinder temperature with fuel-air ratio; dishpan blower; 2200 rpm; 32 inches manifold pressure; corrected to 100° carburetor temperature.

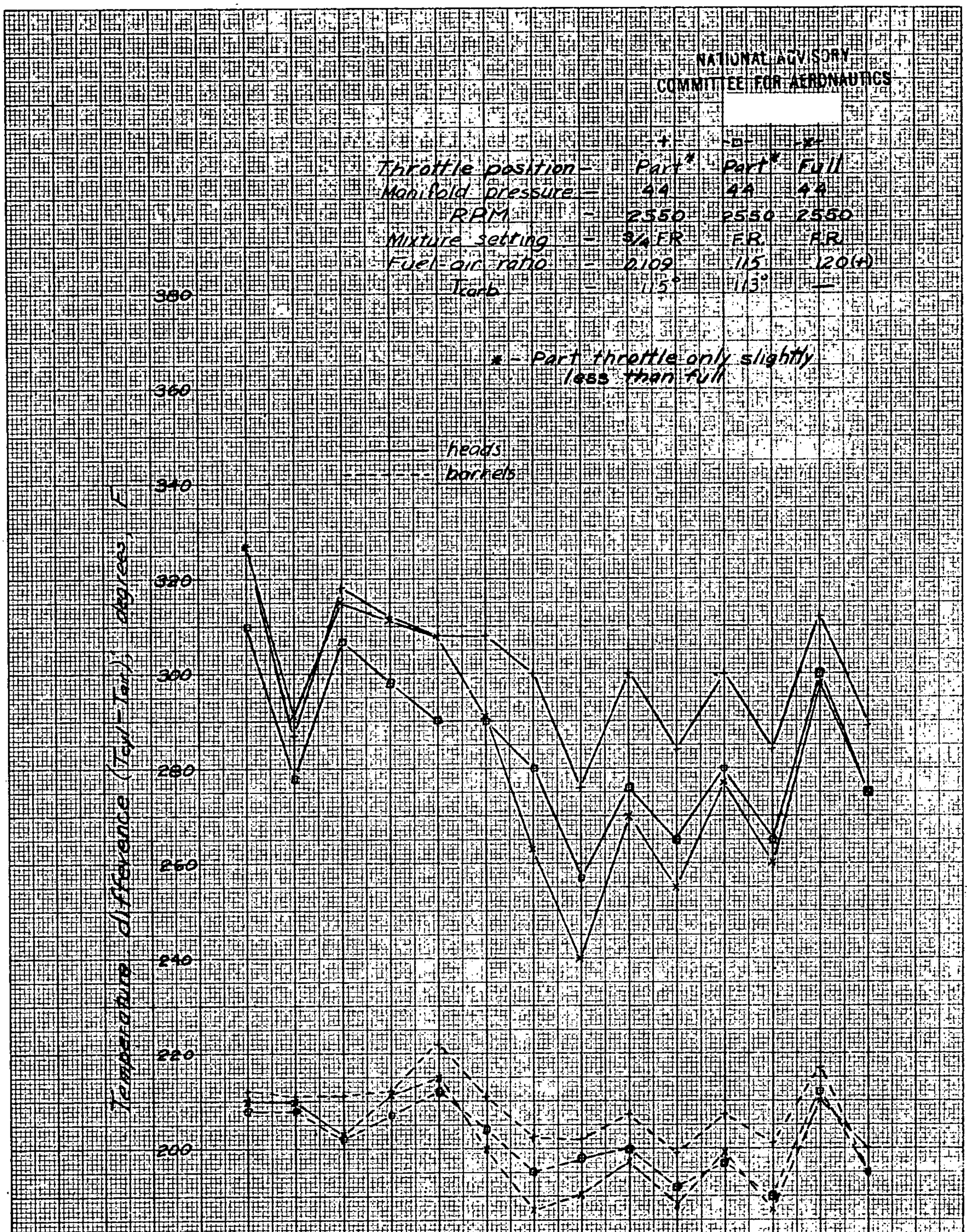


Figure 67. - Variation in head and barrel temperatures with throttle position.

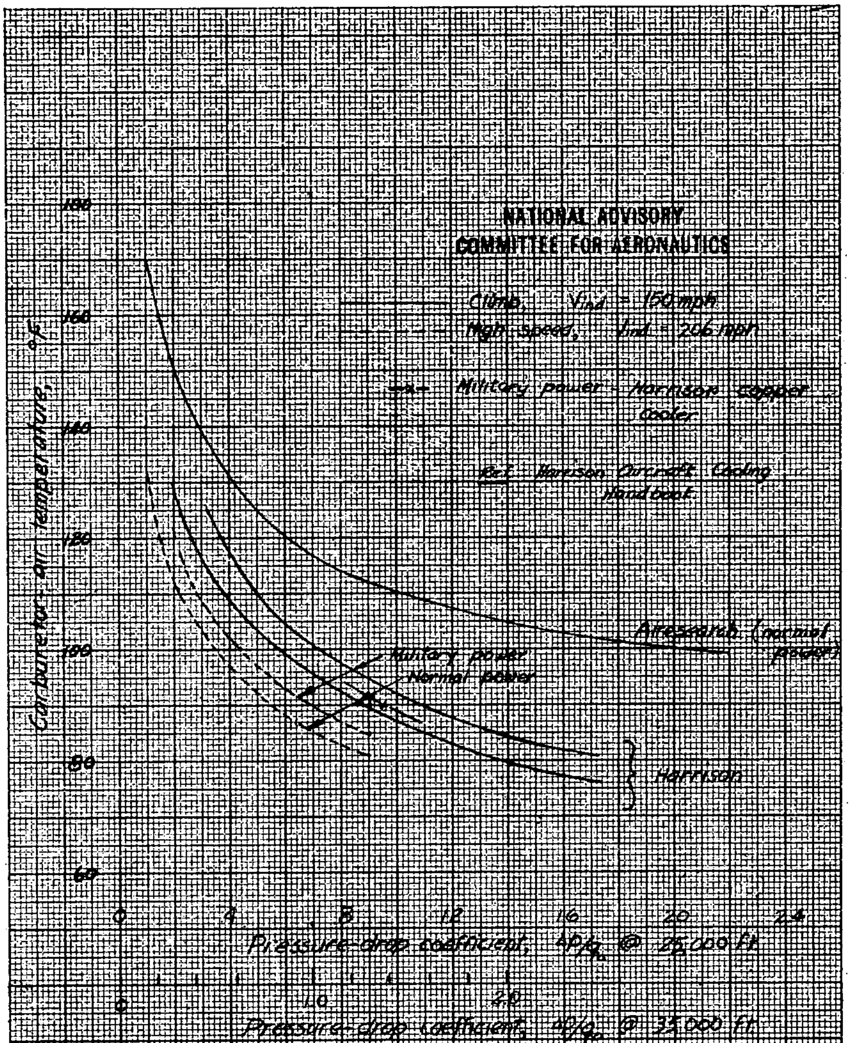


Figure 6d. - Variation of carburetor-air temperature with pressure drop on cooling-air side of the intercooler; Army air.

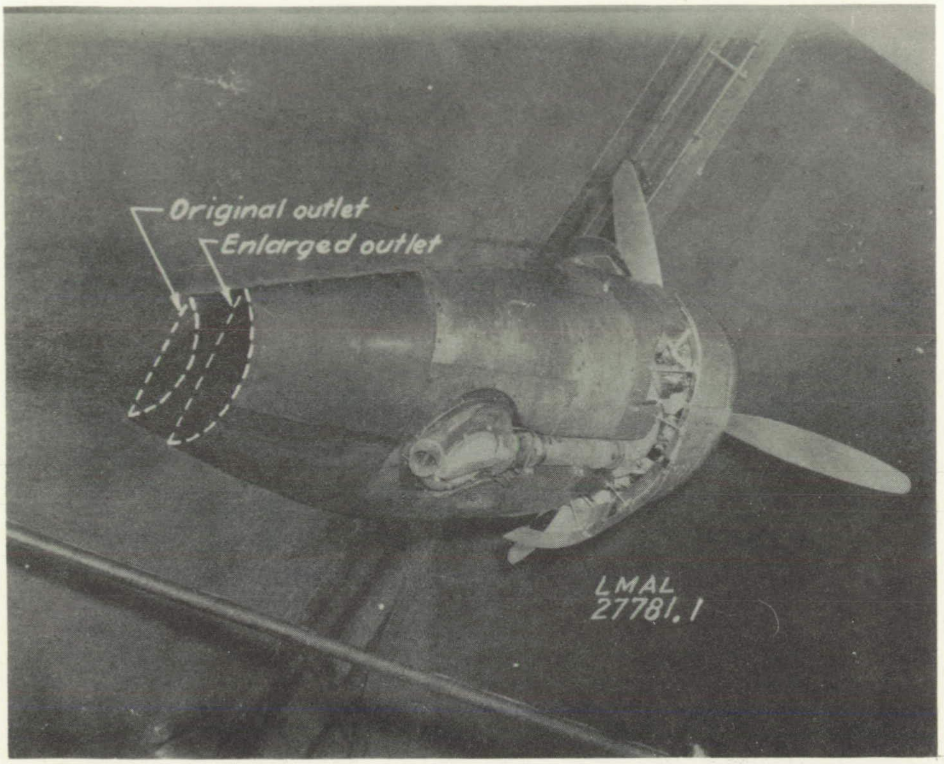
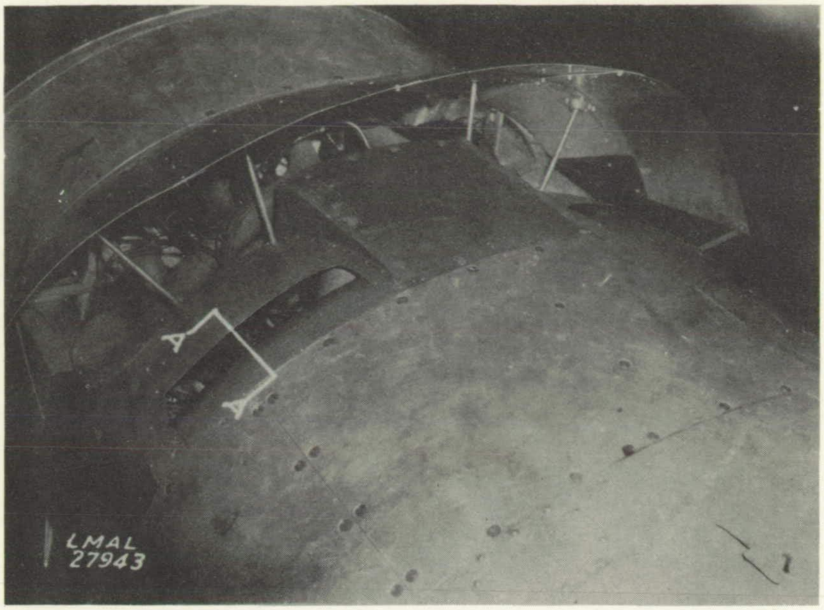


Figure 69.- Bottom view of the B-24D nacelle showing the original and the enlarged nacelle outlet.



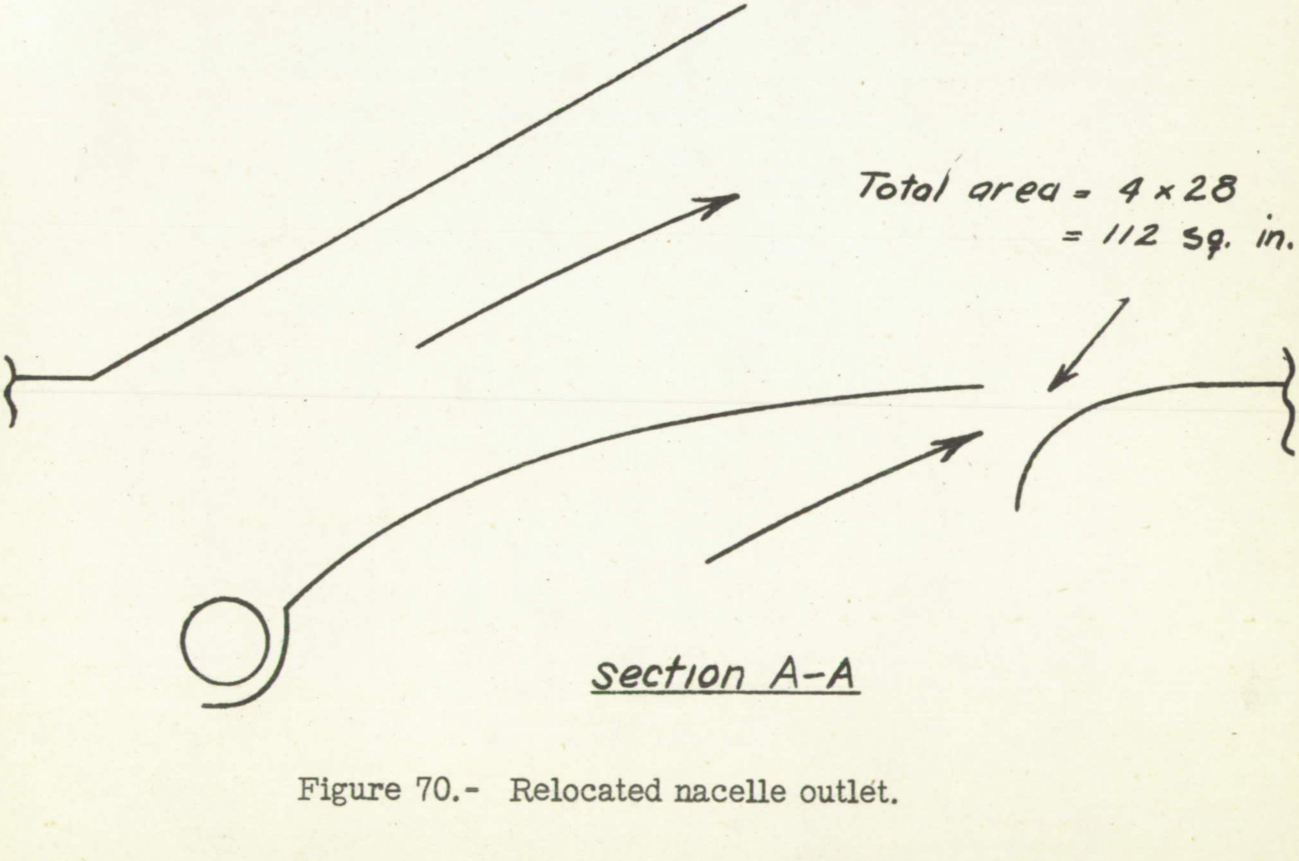


Figure 70.- Relocated nacelle outlet.

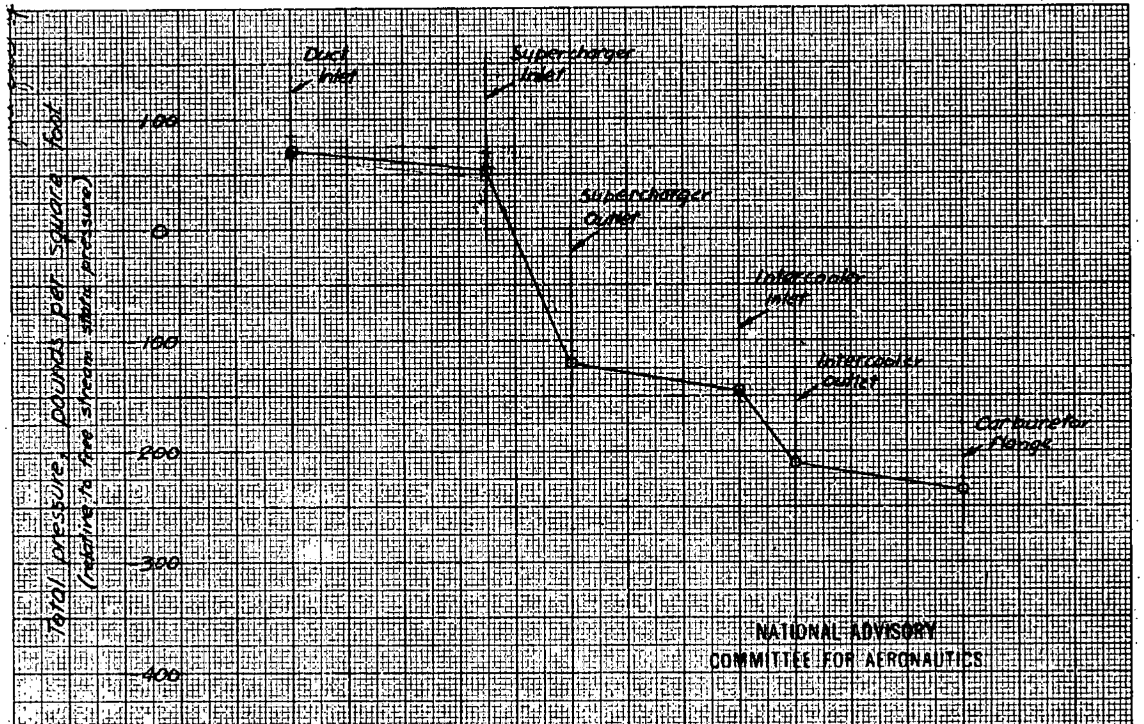


Figure 71. - Total pressure variation in the engine-air induction system for rated power climb at 150 miles per hour. Air flow, 8250 pounds per hour; density, ρ = 0.00238; turbo waste gate full open. Test points corrected to an assumed inlet ram of 70 pounds per square foot at 150 miles per hour.

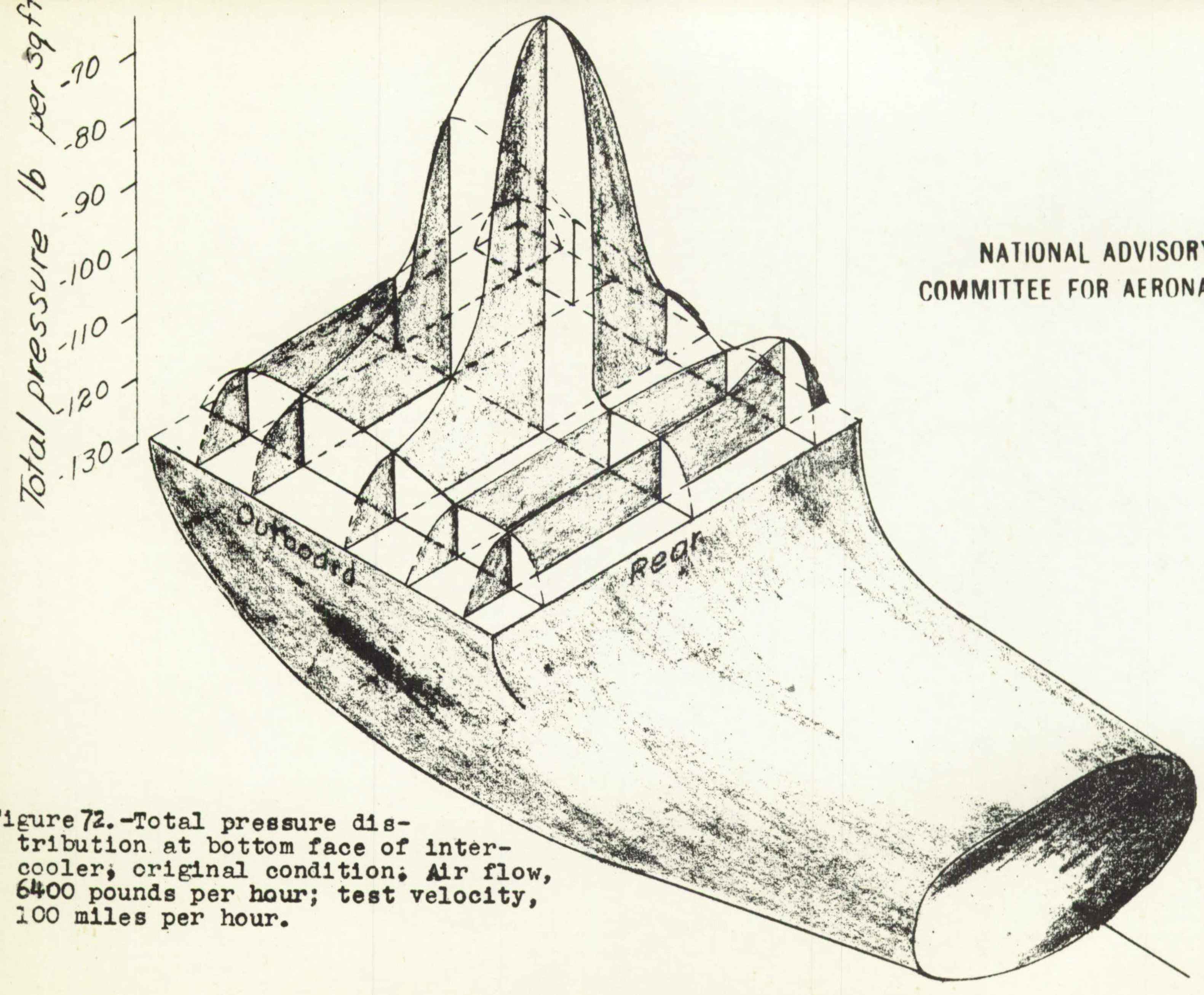


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Figure 72.-Total pressure distribution at bottom face of intercooler; original condition; Air flow, 6400 pounds per hour; test velocity, 100 miles per hour.

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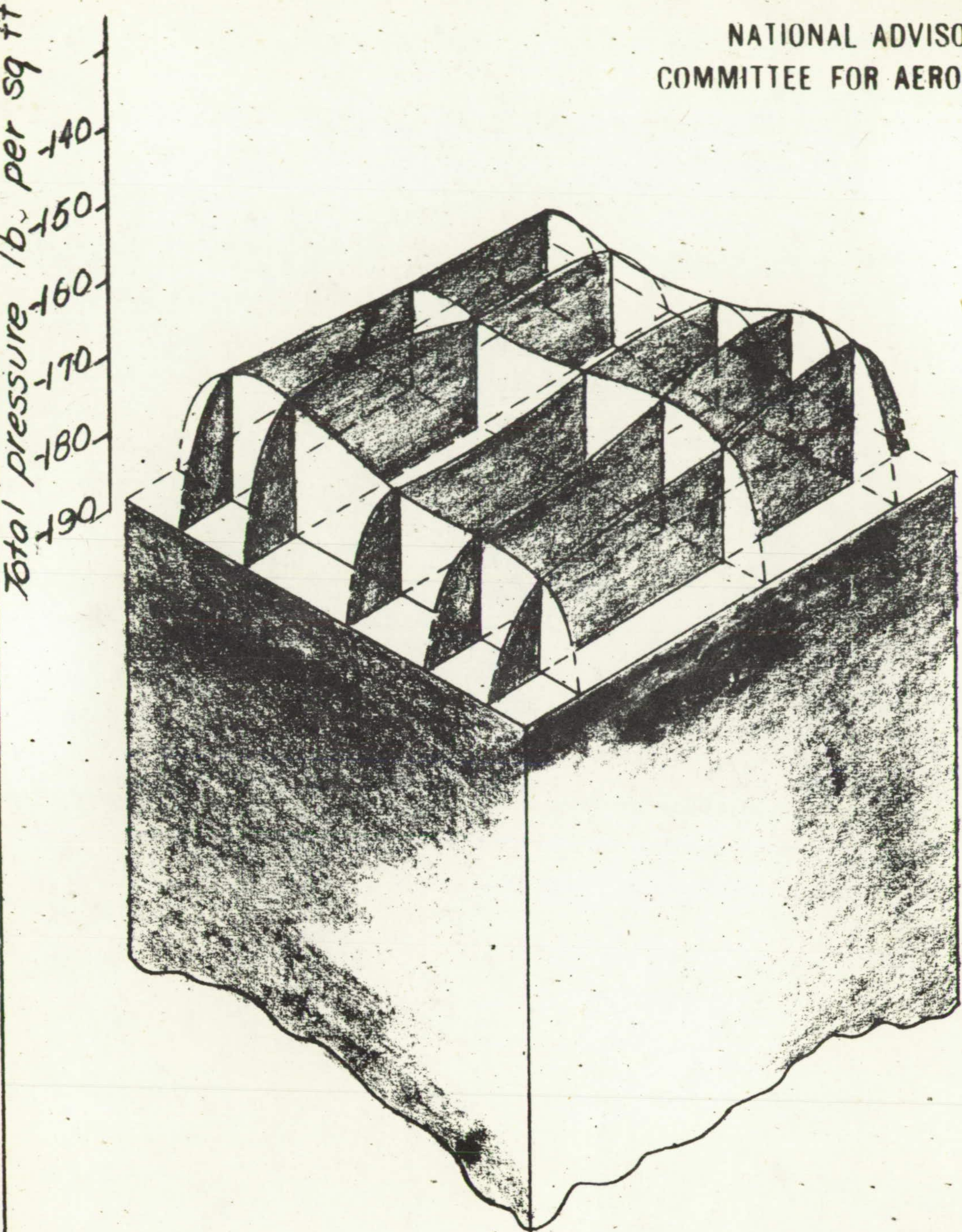

Figure 73.-Total pressure distribution at top outlet of inter-cooler, original condition. Air flow, 6400 pounds per hour; test velocity, 100 miles per hour.

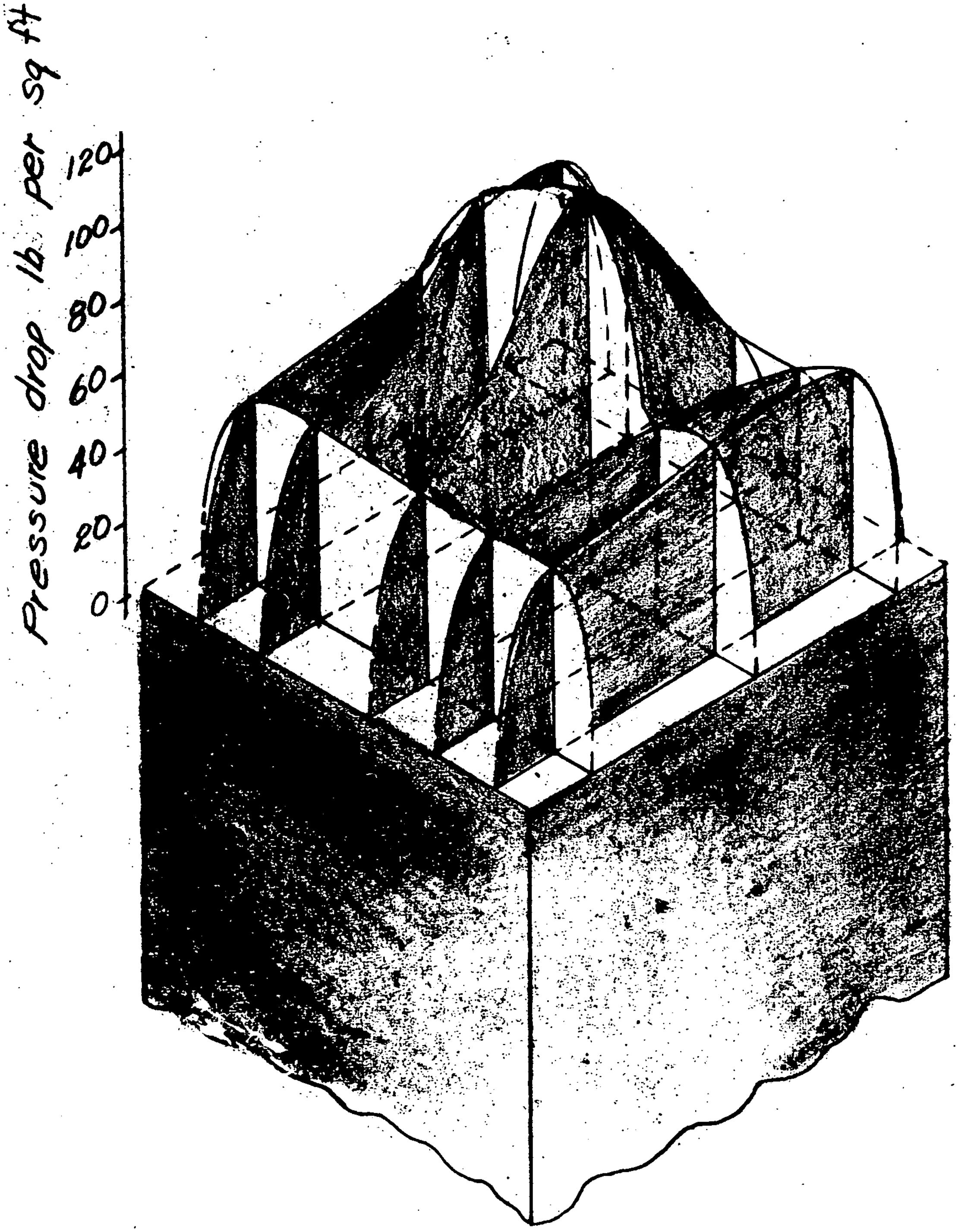

Figure 74.-Pressure drop across intercooler, original condition. Air flow, 6400 pounds per hour; test velocity, 100 miles per hour.

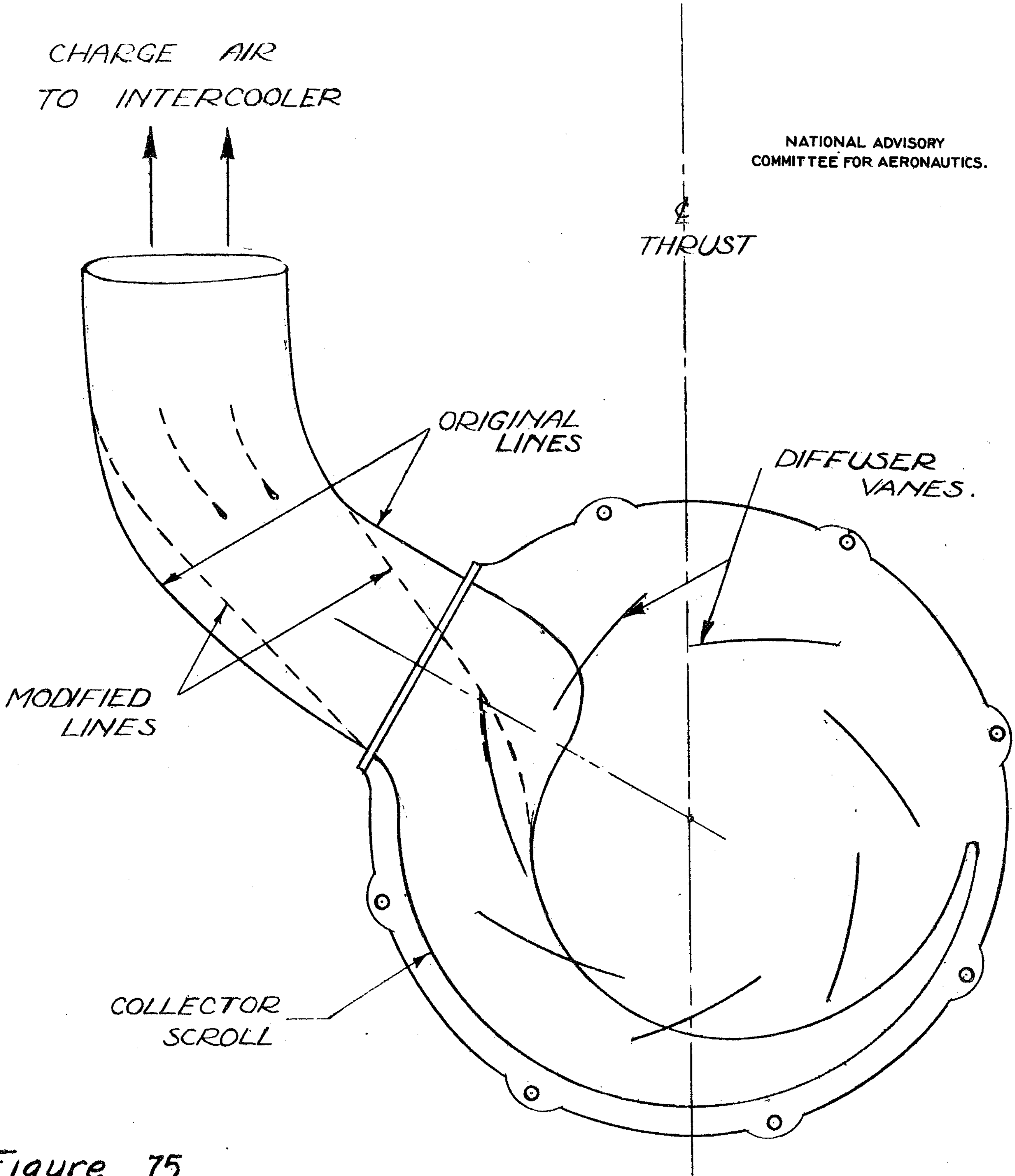

Figure 75

MODIFIED SUPERCHARGER AIR OUTLET

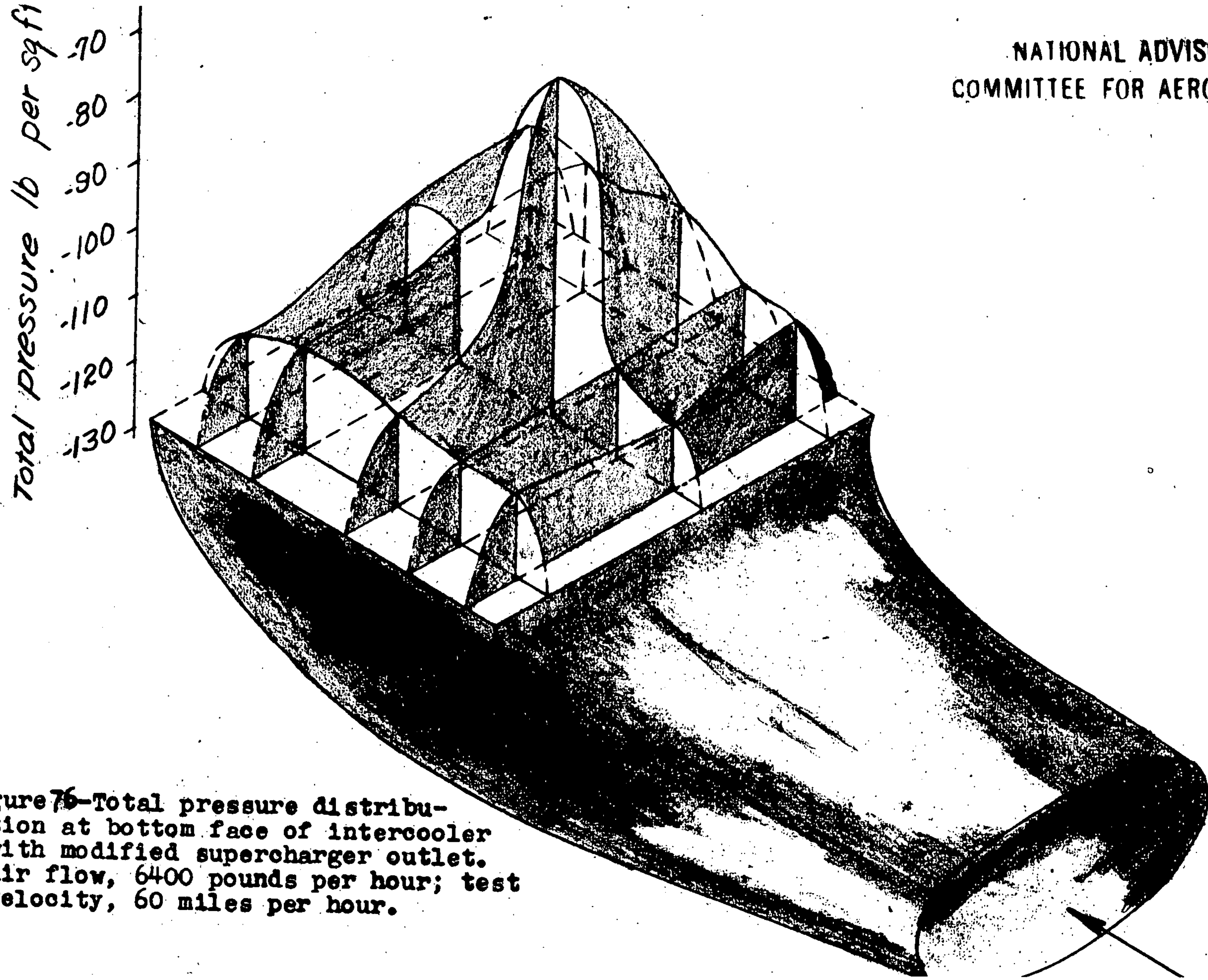

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Figure 76-Total pressure distribution at bottom face of intercooler with modified supercharger outlet. Air flow, 6400 pounds per hour; test velocity, 60 miles per hour.

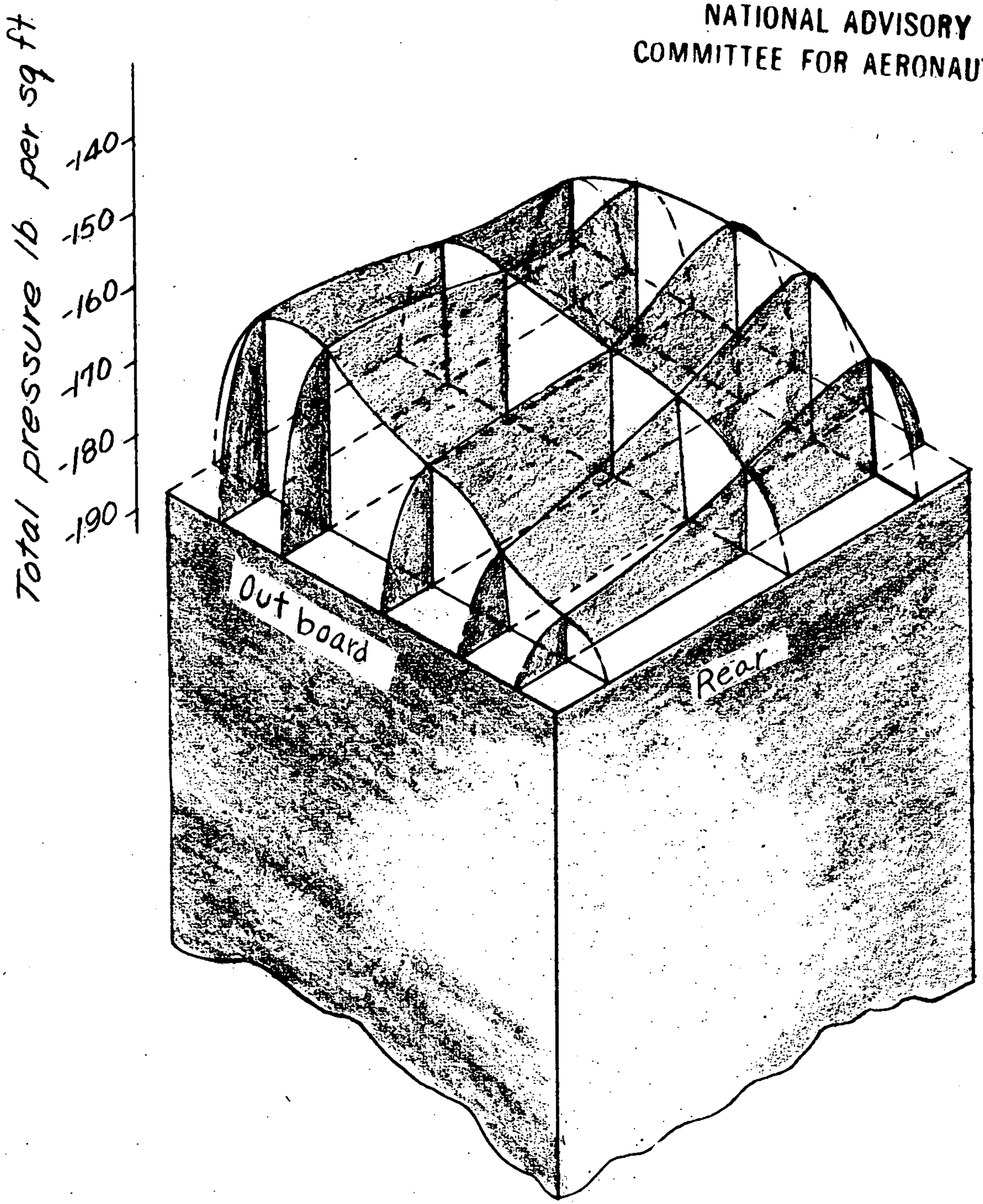

Figure 77.- Total pressure distribution at top outlet of intercooler with modified supercharger outlet. Air flow, 6400 pounds per hour; test velocity, 60 miles per hour.

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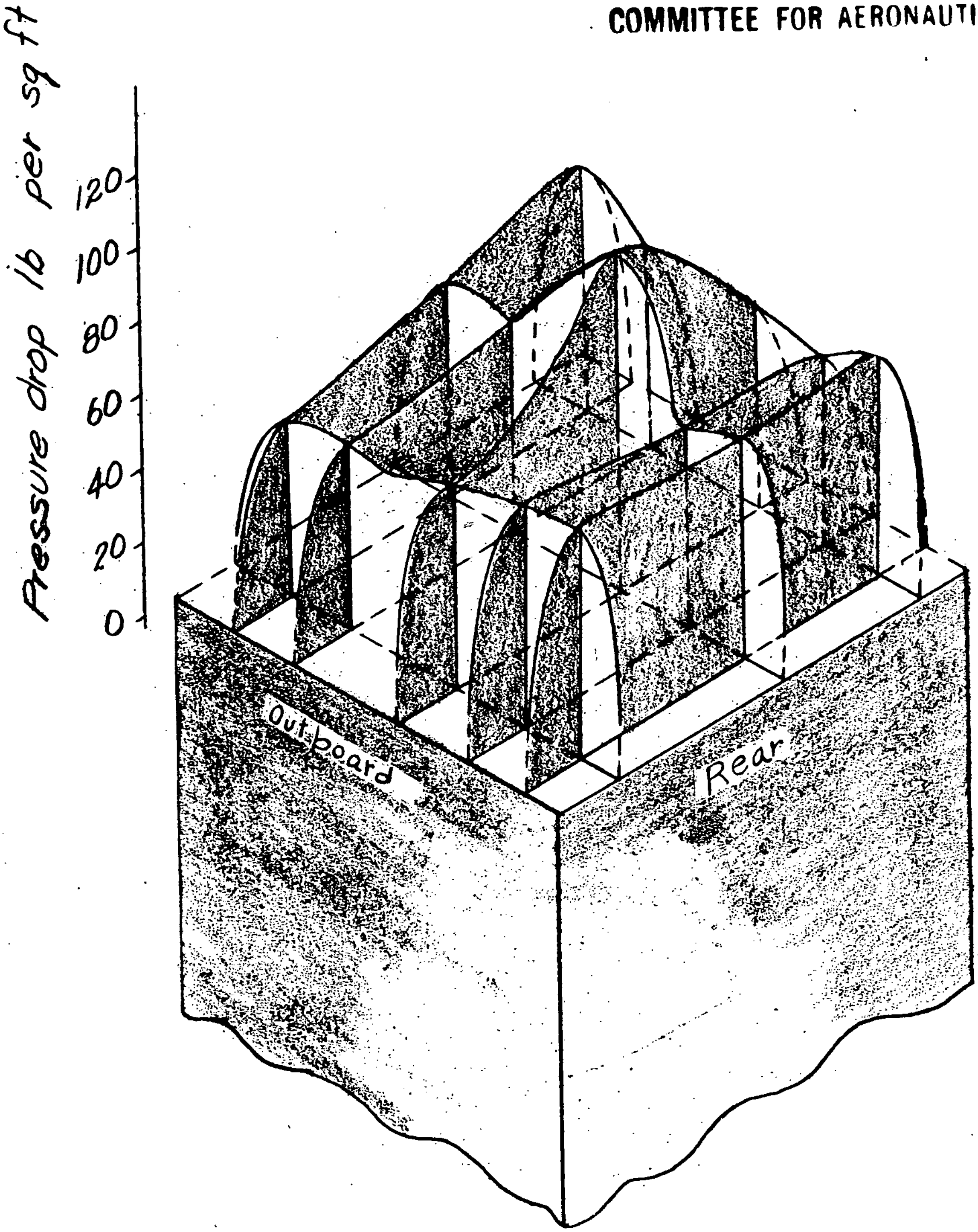


Figure 78.-Pressure drop across charge-air side of intercooler with modified supercharger outlet. Air flow, 6400 pounds per hour; test velocity, 60 miles per hour.

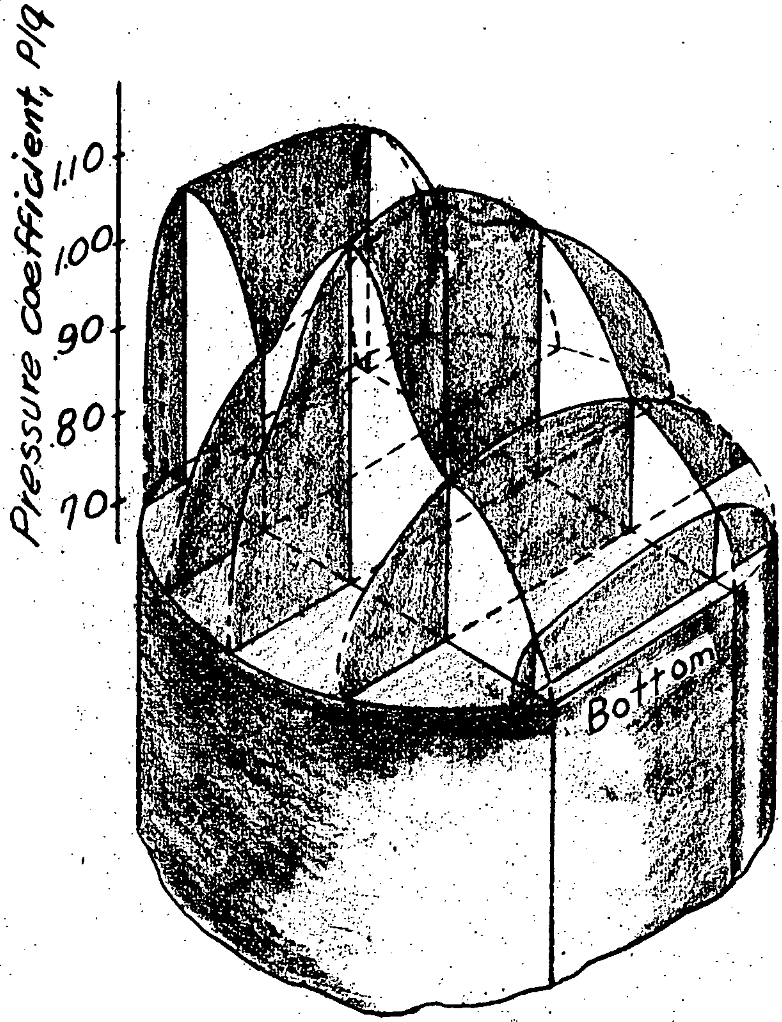


Figure 79.- Typical total pressure distribution at inlet of B-24D oil cooler in the climb condition.

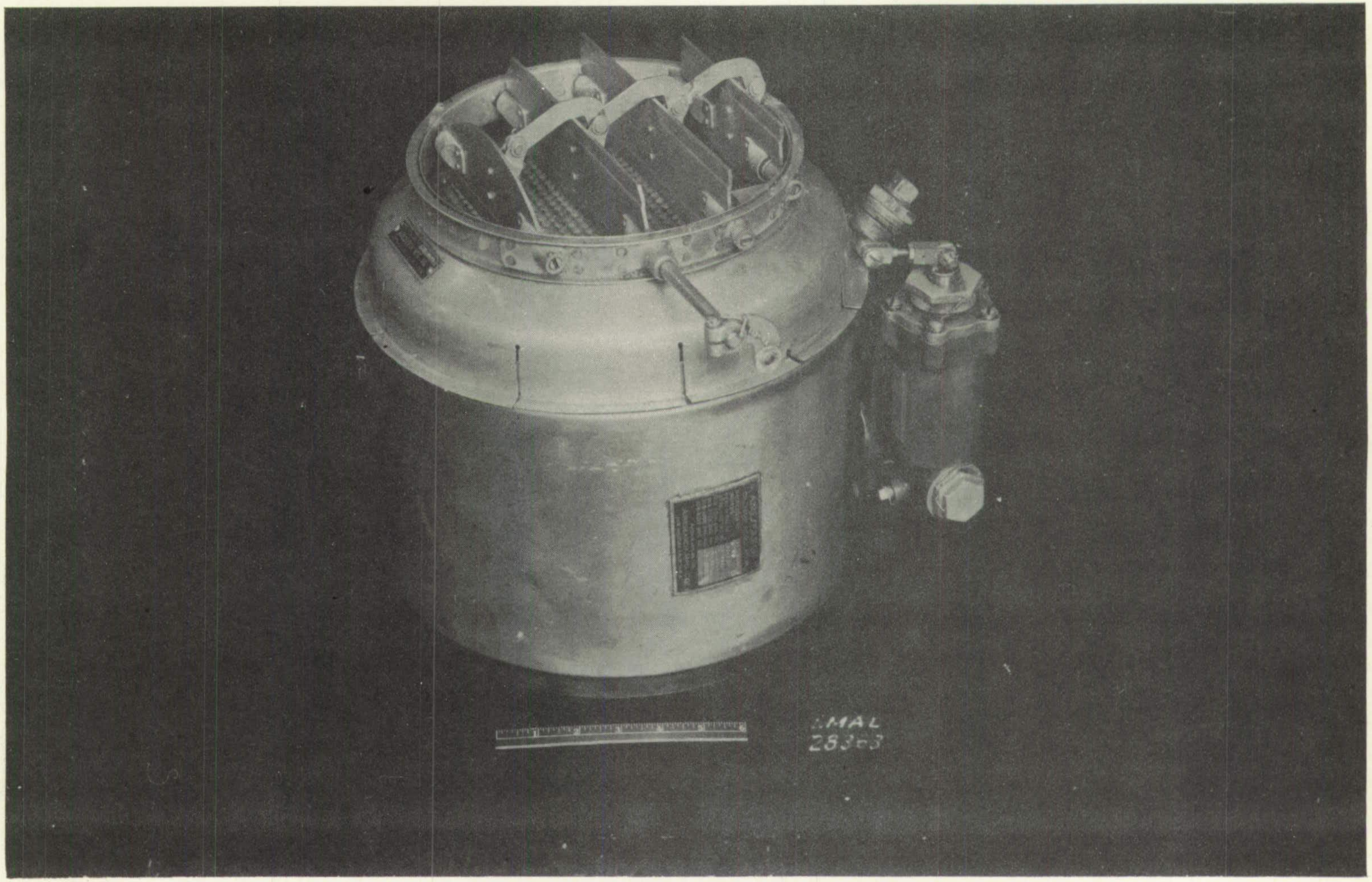
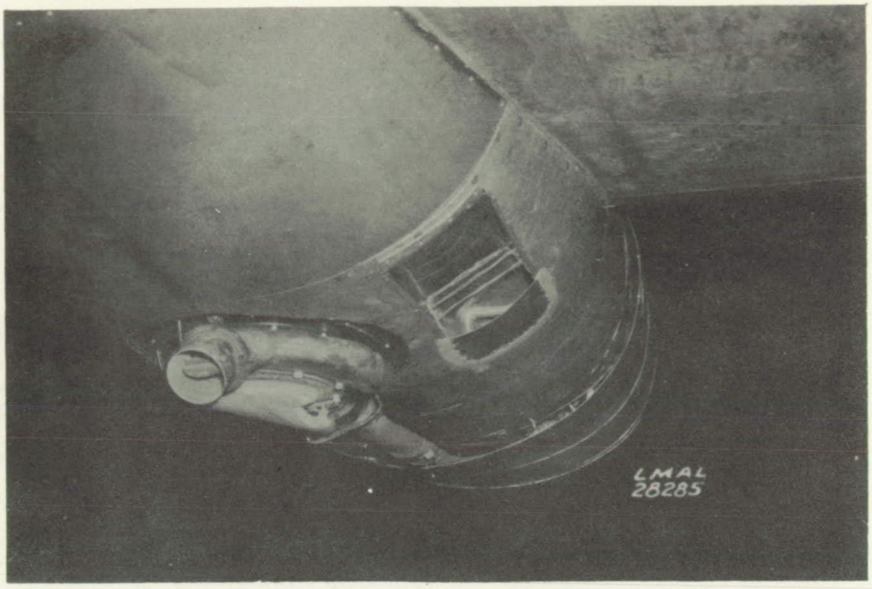
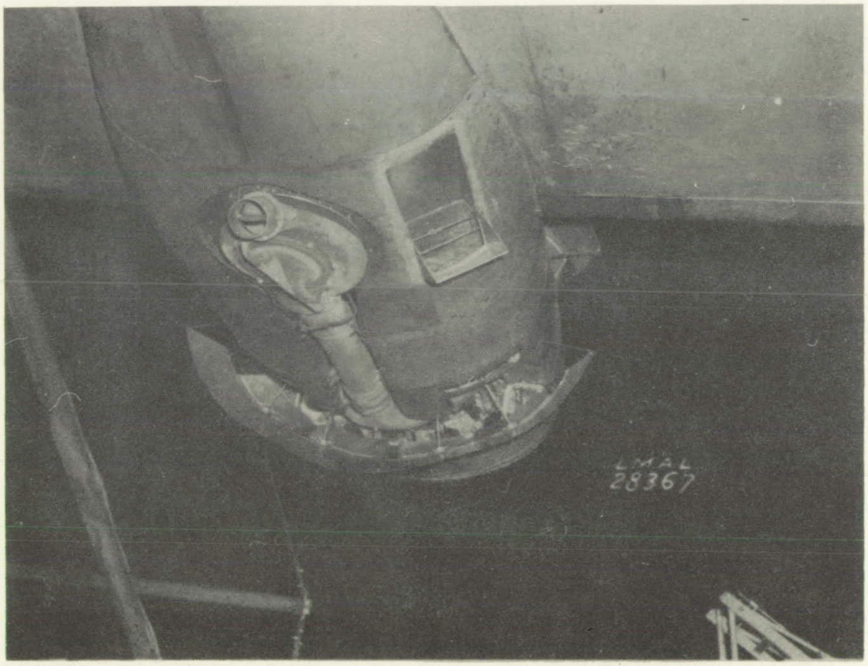


Figure 80.- Oil cooler with the shutters installed.



(a) Oil-cooler flap closed.



(b) Oil-cooler flap open.

Figure 81.- Bottom view of the B-24D nacelle with the separate oil-cooler outlet.

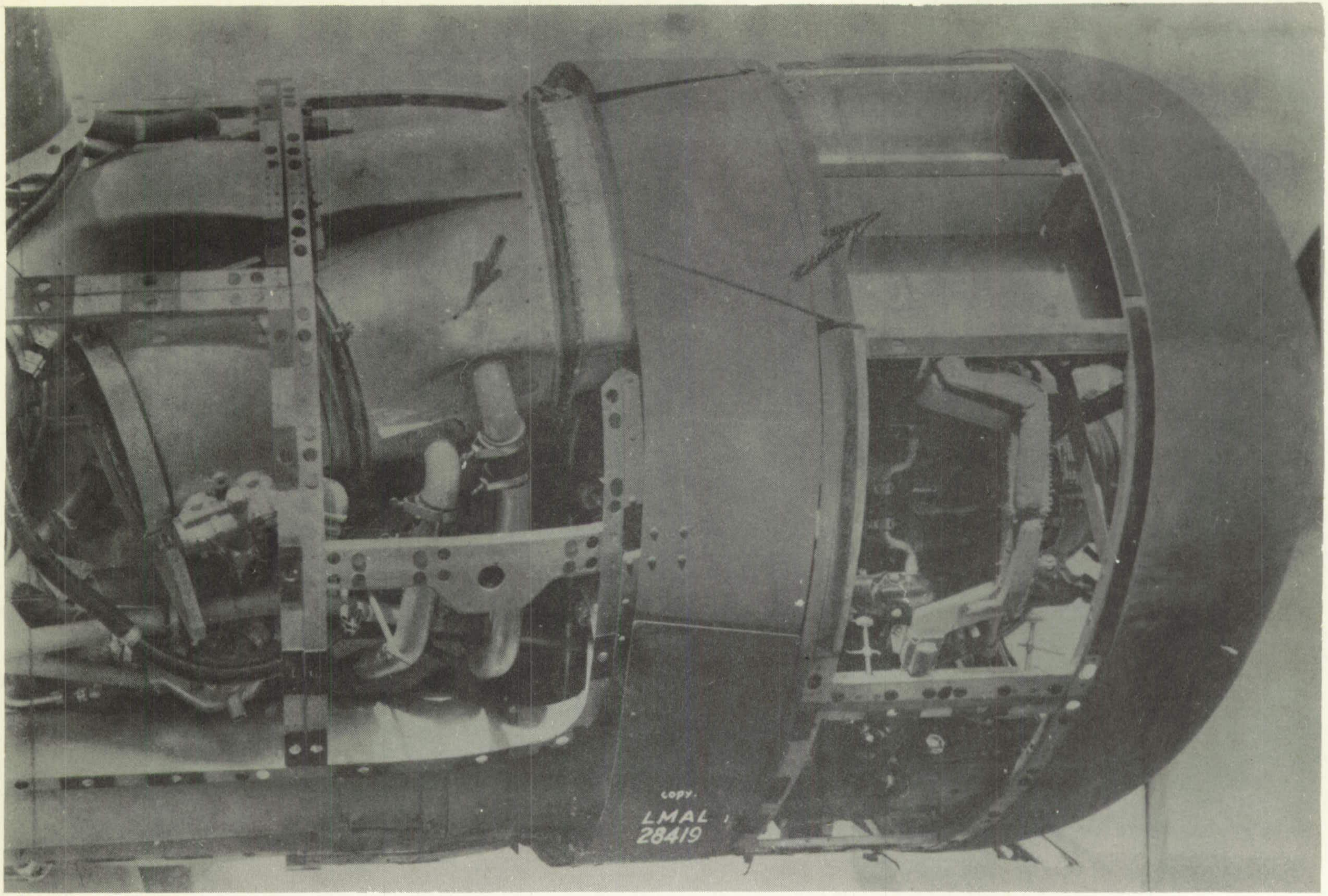
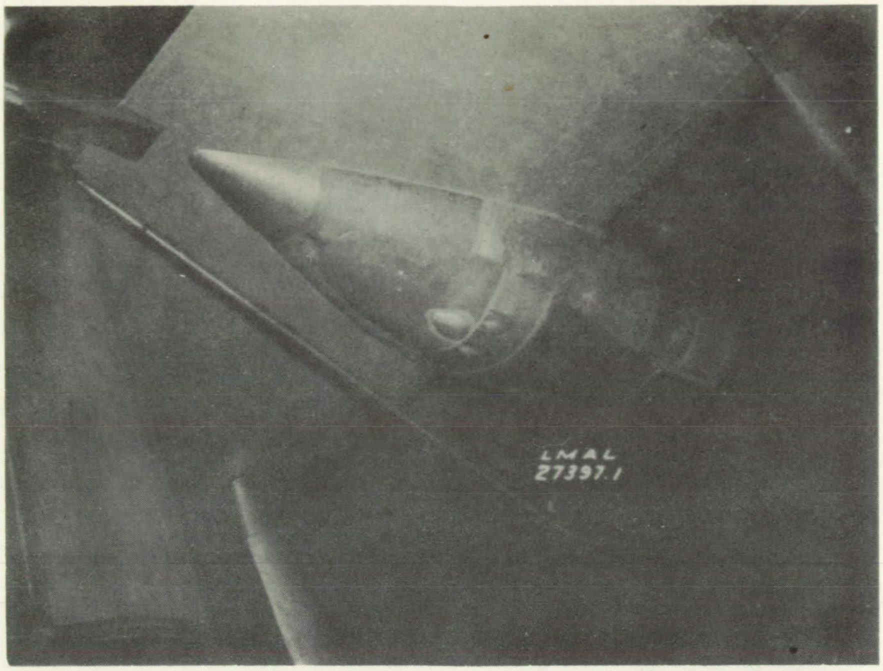


Figure 82.- Side view of B-24D nacelle showing vanes which were removed to improve flow through the oil cooler.



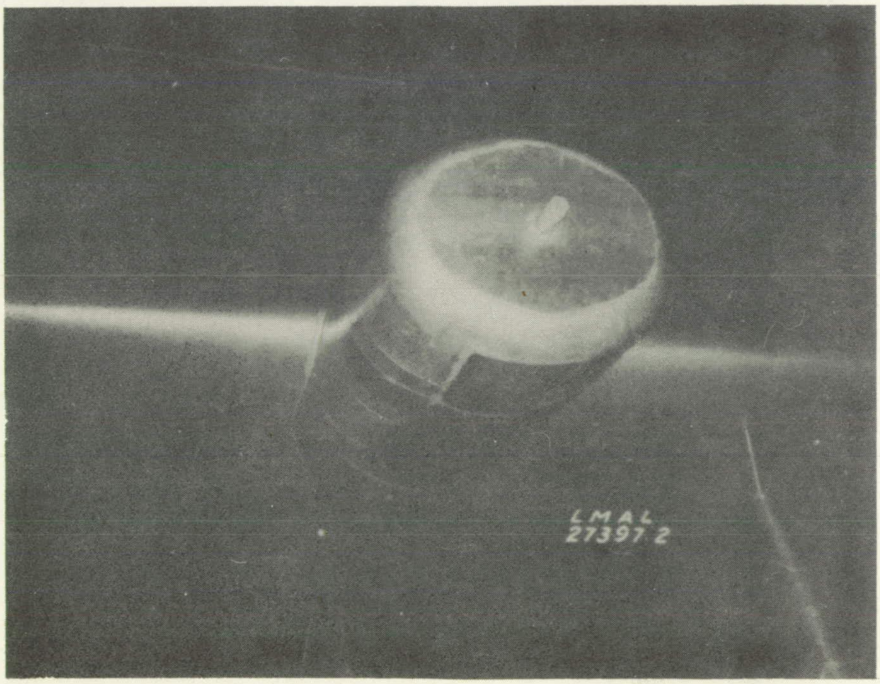


Figure 83.- Front and side view of B-24D nacelle completely faired.

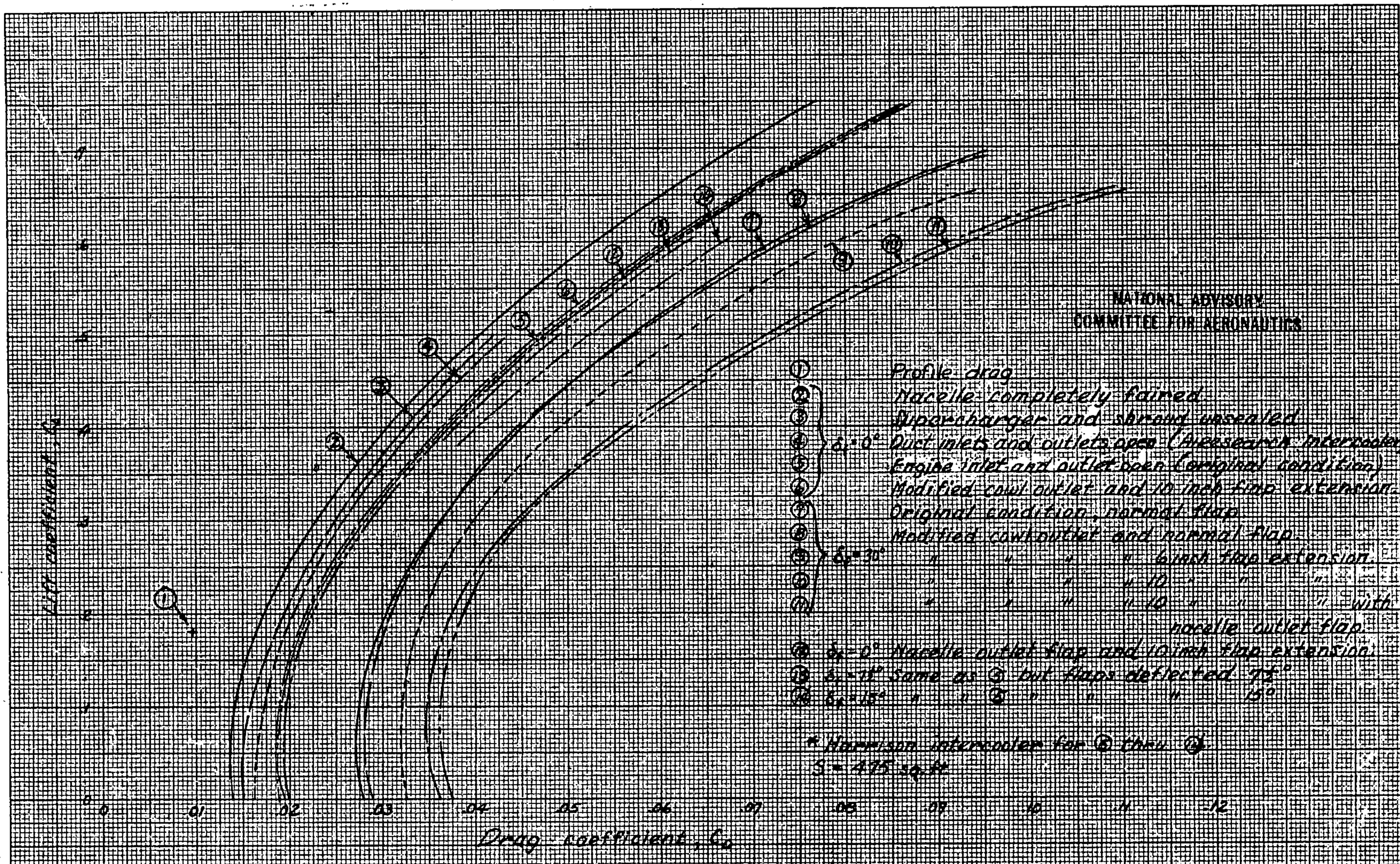


Figure 34.- Power-off lift and drag polars.

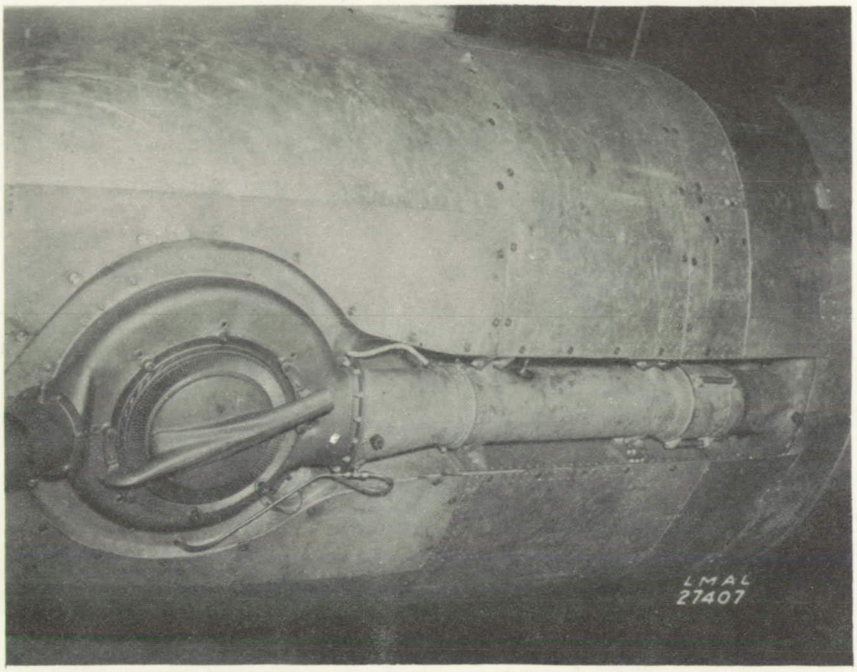


Figure 85.- Bottom view of the B-24D nacelle with supercharger and exhaust pipe ahead of supercharger unsealed.

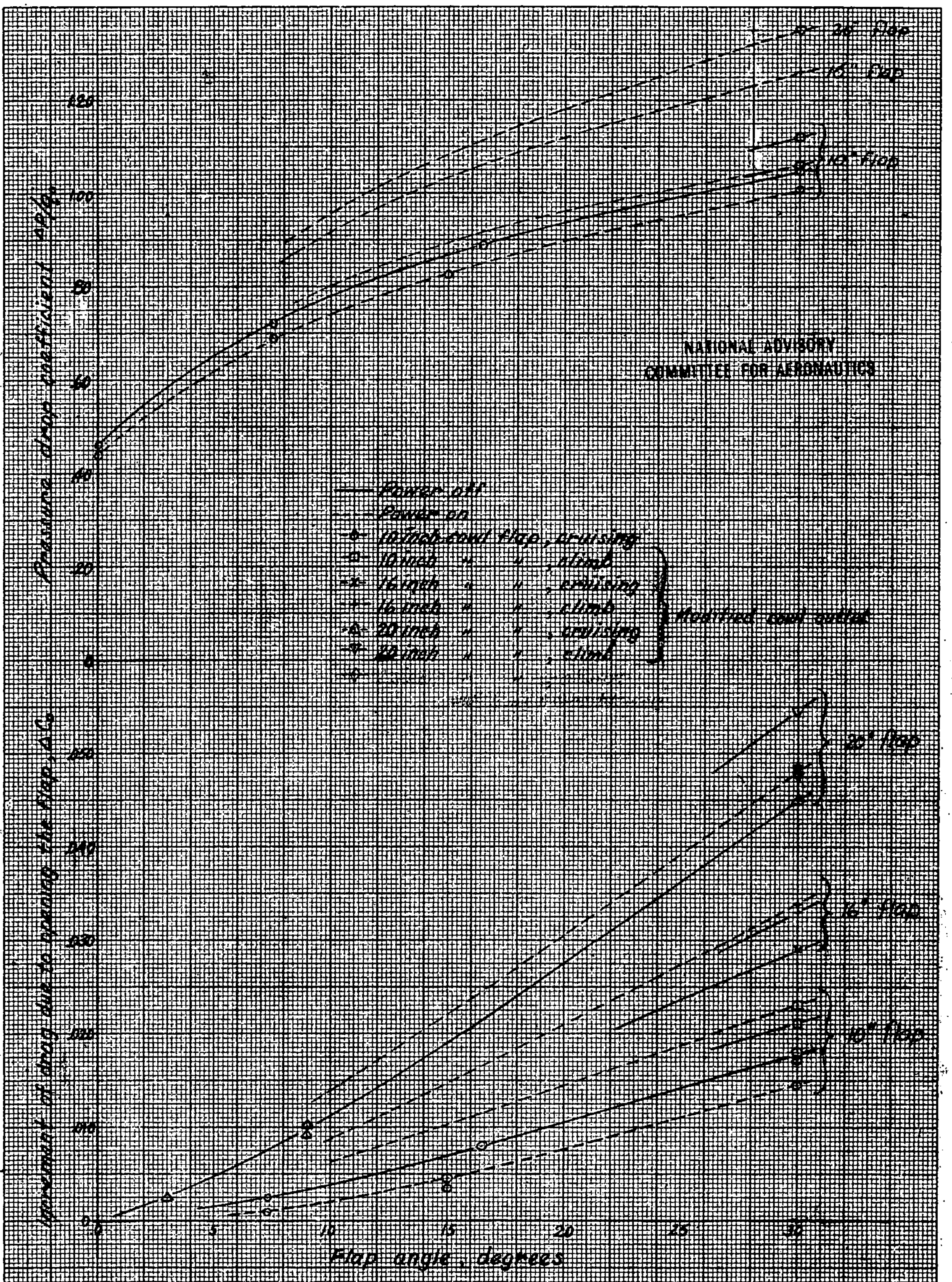
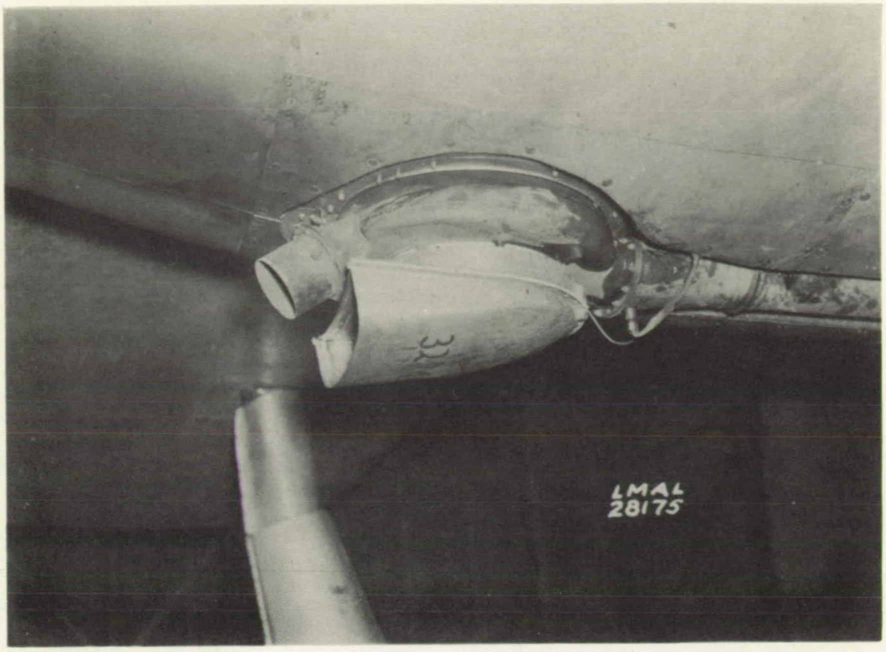


Figure 86. - Variation of the drag and the engine pressure drop with flap angle in cruising and climb attitudes.



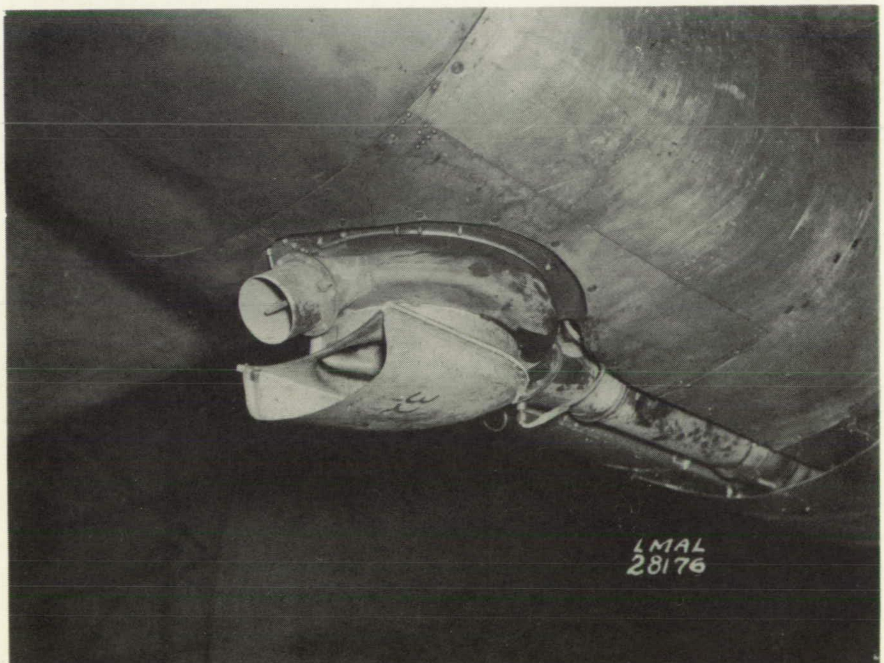


Figure 87.- Bottom view of B-24D nacelle showing the hood installed on the turbine.

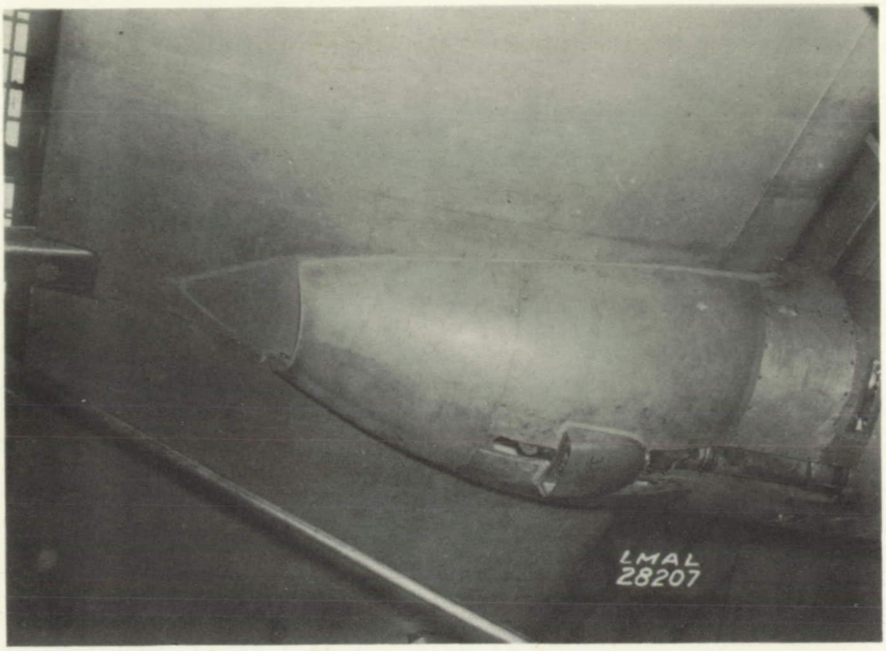


Figure 88.- Bottom view of the B-24D nacelle with the new afterbody as originally installed.

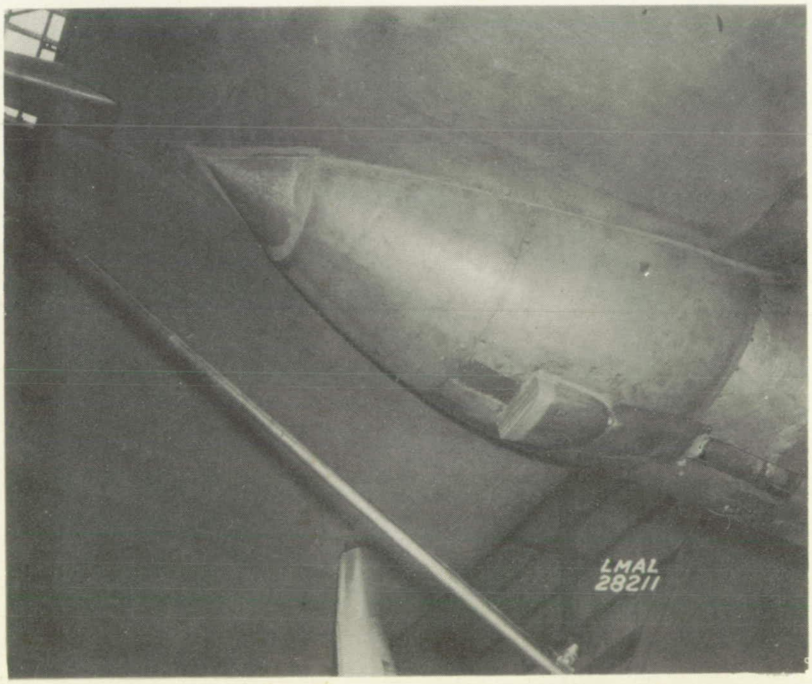


Figure 89.- Bottom view of B-24D nacelle with the leaks and gaps in the new afterbody sealed.

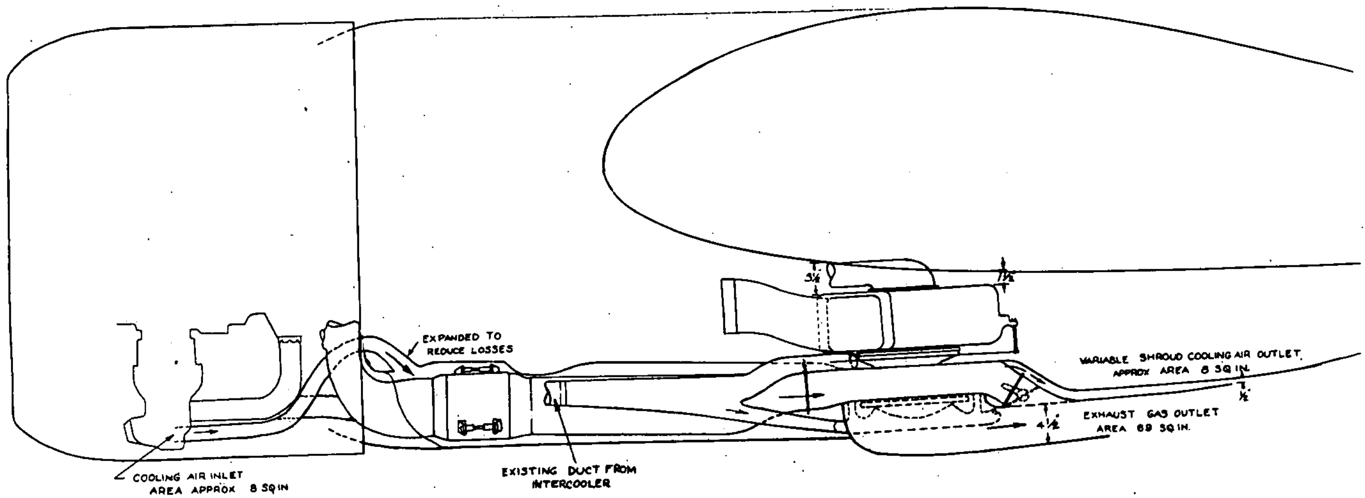


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Figure 90. - Suggested turbosupercharger installation for the B-24D engine-nacelle installation.

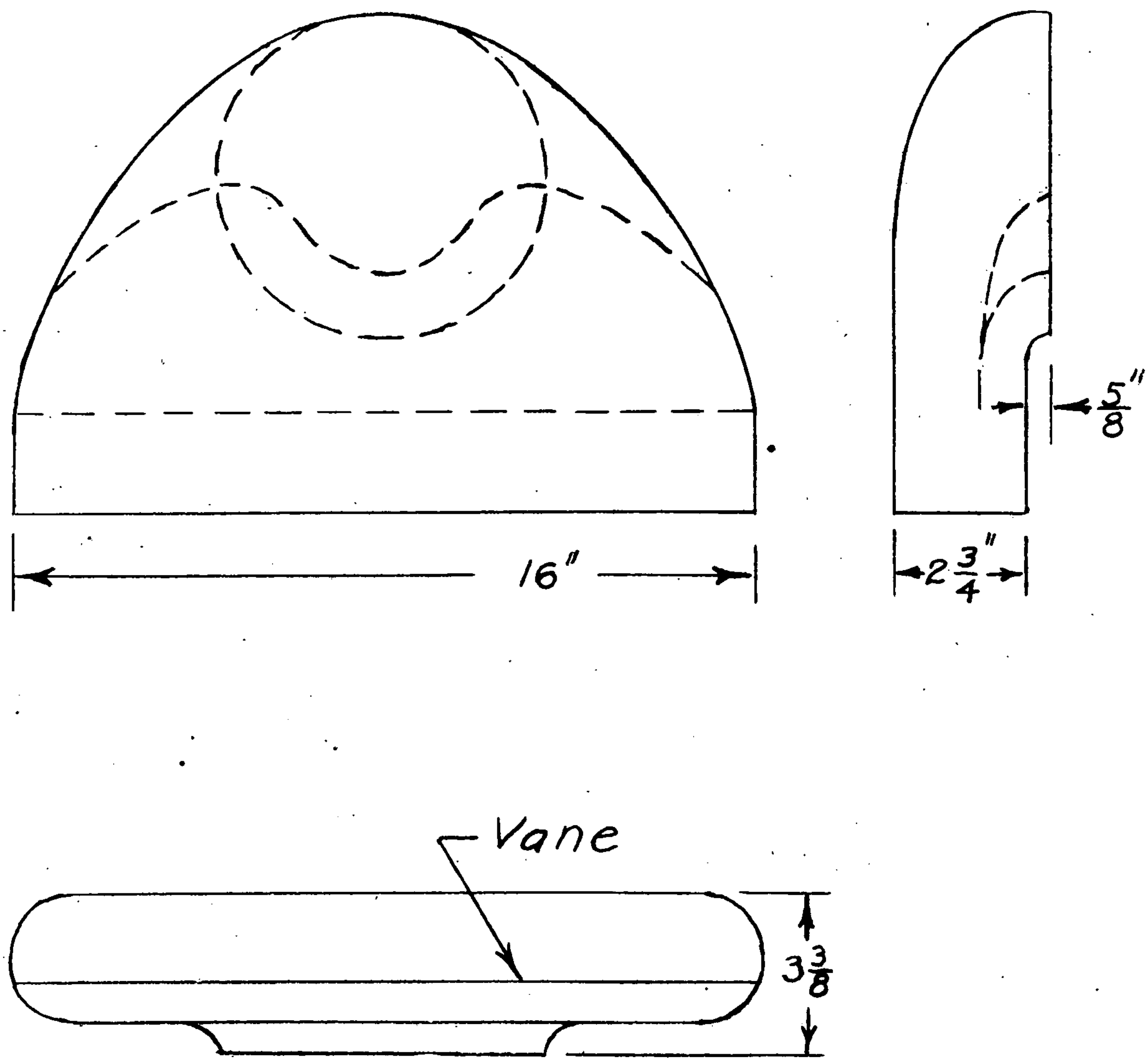

Figure 91. - Compressor inlet elbow recommended for use with the revised supercharger installation.

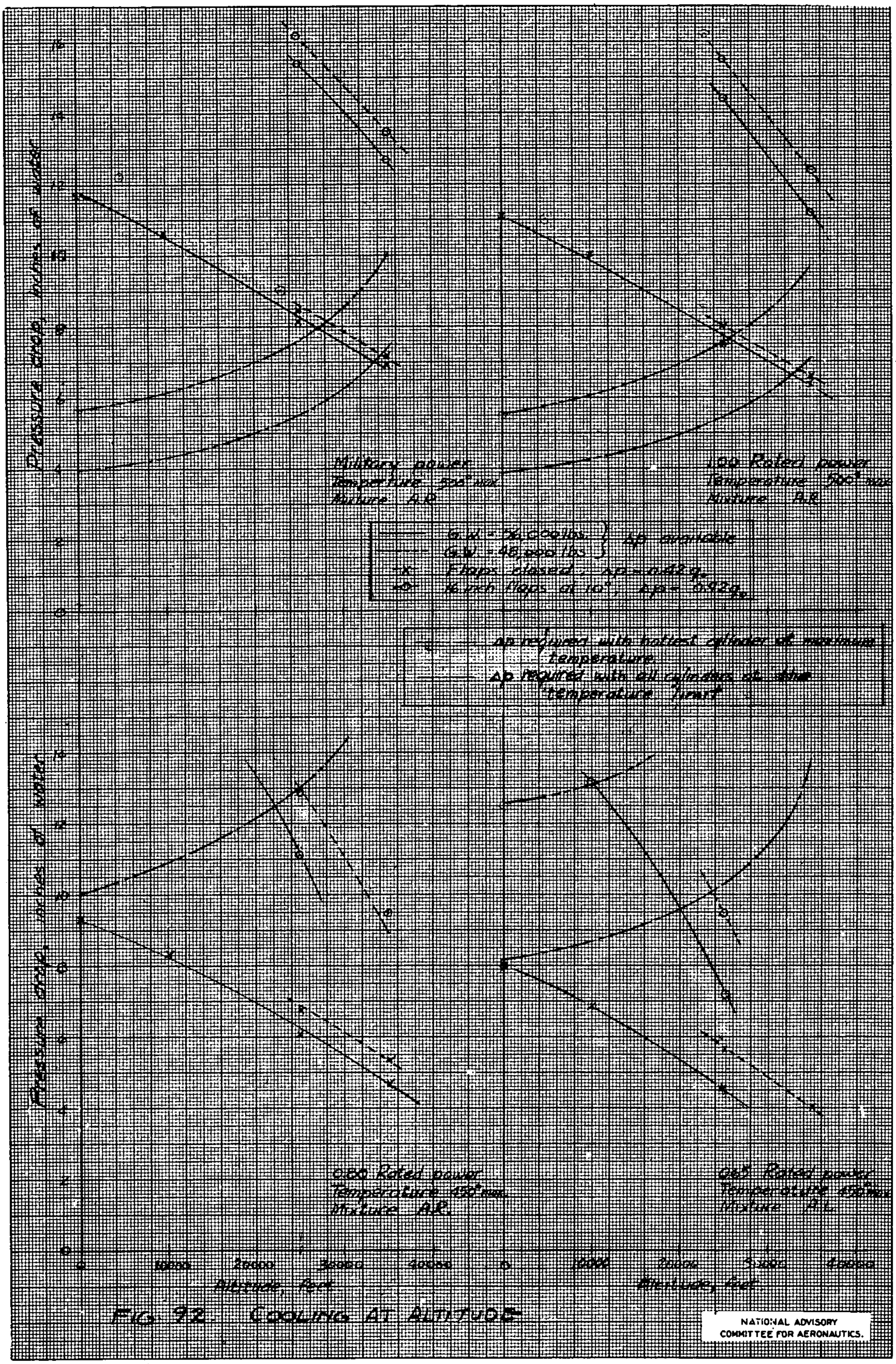

FIG. 92. COOLING AT ALTITUDE